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PALEOZOIC CORDILLERAN GEOSYNCLINE AND RELATED OROGENY

A. J. EARDLEY
University of Michigan

ABSTRACT

The Cordilleran geosyncline in Paleozoic time consisted of two main troughs—a western, the Pacific, and an eastern, the Rocky Mountain. The sediments of the western trough from California to Alaska are characterized by a large amount of volcanic material and graywacke in every system. Phyllites, slates, argillites, schists, gneisses, recrystallized chert, marble, metaconglomerate, meta-andesite, and various metamorphosed pyroclastics make up the thick sequences. Great batholiths of Mesozoic age invaded the sediments of the Pacific trough; but in only one place, the Idaho batholith, did they reach the Rocky Mountain trough.

Dynamic metamorphism and the great intrusives, together with blanketing Cenozoic deposits, have left the medial area between troughs little known. The Rocky Mountain trough contains mostly marine limestones, shales, and sandstones. Many of the sands are cemented with silica and termed "quartzite," but little metamorphism has occurred, and none has been assigned to Paleozoic orogeny.

The volcanic materials are nearly all andesites and came from the west. Since the sites of extensive accumulation of andesitic flows and debris today are in troughs adjacent to island archipelagos, it is suggested that a volcanic archipelago flanked the Pacific trough on the west. The Paleozoic graywackes and conglomerates also came from the west and from Paleozoic rocks already metamorphosed before erosion. Several angular unconformities indicate orogeny in the belt to the west. The island archipelago was therefore a site of continuing orogeny during the Paleozoic. It was very similar to the island arcs of the present Japanese archipelago.

Instead of a rigid land of continental proportions, with a shore in western Montana, a volcanic orogenic archipelago is believed to have existed, which for the most part lay west of our modern coast.

PALEOZOIC CORDILLERAN GEOSYNCLINE

DIVISIONS AND THEIR CHARACTERISTICS

Charles Schuchert[1] is probably more responsible than anyone else for the use of the expression "Cordilleran geosyncline" in describing the basins of accumulation of sediments along the western part of the continent. He also used the term "Rocky Mountain geosyncline." The sediments of the seaways that shifted over the entire western third of the continent from the Dakotas to California were included. During the Mesozoic his "Cordilleran intermontane geanticline" split the over-all broad and irregular basins into two "geosynclines"—a western and an eastern. He emphasized the changes in the shorelines of the seaways, whereas in the following pages the troughs of maximum subsidence and the sediments in them will receive special attention.

In Paleozoic time the Cordilleran geosyncline consisted in a very general way of two main troughs, a western, here called the "Pacific," and an eastern, the Rocky Mountain (see Figs. 1 and 2). The medial area was also one of heavy sedimentation, but not much is known about it, especially in Canada.

[1] *Historical Geology* (several eds.; New York: John Wiley & Sons).

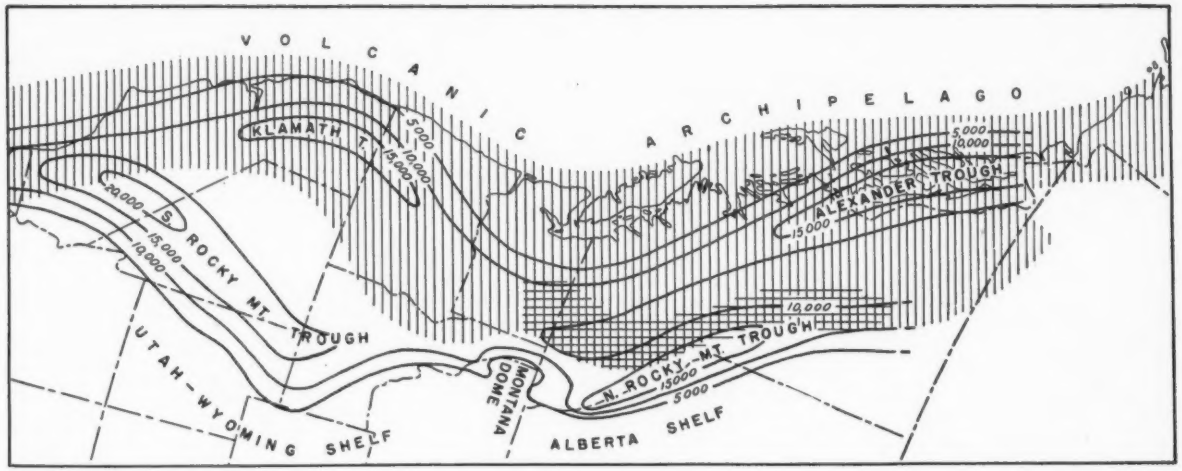


FIG. 1.—Pre-Devonian Paleozoic troughs of the Cordilleran geosyncline. The horizontally ruled area represents the distribution of the volcanic archipelago assemblage of sediments. The cross-ruled area is the Shuswap terrane.

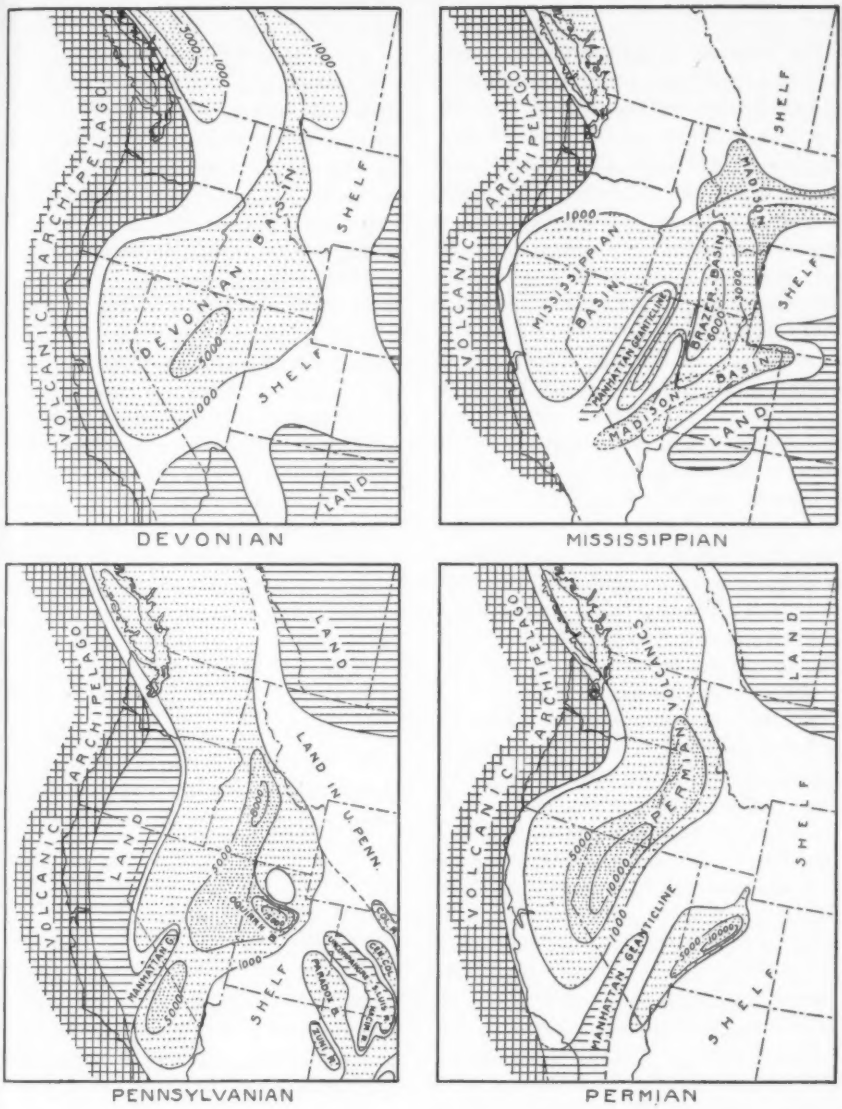


FIG. 2.—Paleotectonic maps of the Cordilleran region in late Paleozoic time. Cross-ruled area is the volcanic archipelago and orogenic belt. Horizontally ruled areas were uplifted and eroded during the period designated. White areas sank and were covered with less than 1,000 feet of sediments (after consolidation). Lightly stippled areas sank sufficiently to be covered with more than 1,000 feet of sediments. Denser stippling denotes areas that sank more than 5,000 feet, except on the Mississippian map, where it distinguishes the Madison (Lower Mississippian) from the Brazer (Upper Mississippian). The "lands" of each period are areas that actually rose and are not those simply that remained above sea level as a result of a previous uplift.

The western trough probably sank more and received a greater thickness of sediments than did the eastern, but the extent of sediments in both was of geosynclinal proportions. The greatest difference lies in the character of the sediments. The Pacific trough received a dominant amount of volcanic material and graywacke, whereas the Rocky Mountain trough was filled with sandstones, shales, and limestones. The volcanic material in the Pacific trough is in several forms—tuffs, flows, volcanic conglomerates, and various pyroclastics. The volcanics and graywackes occur in every stratigraphic system from Ordovician and older to Cretaceous. The Permian especially was a time of excessive volcanism, and the volcanics of that period have been traced from California and western Nevada to Alaska.[2] In the Humboldt Range of northwestern Nevada, over 10,000 feet of Permian strata, largely volcanic, have been identified.

Another characteristic of the sediments of the Pacific trough is their metamorphism. Phyllites; slates; argillites; quartz, chlorite, hornblende, and calcareous schists; hornblende gneiss; recrystallized chert; marble; metaconglomerate; meta-andesite and various metamorphosed pyroclastics make up the thick sequences. Still another characteristic is the presence of great intrusive bodies of a later age and the metamorphism of the sediments about the intrusions.

The sediments of the Rocky Mountain trough, on the other hand, are not metamorphosed. Many of the sands are cemented with silica and termed "quartzite," but little dynamic metamorphism incident to Paleozoic, Mesozoic, or Tertiary orogeny has occurred.

[2] H. E. Wheeler, "Permian Volcanism in Western North America," *Proc. 6th Pacific Sci. Cong.*, Vol. I (1939), pp. 369–76.

ROCKY MOUNTAIN TROUGH

Pre-Devonian basins.—The Rocky Mountain trough is noted for its Cambrian sections. At one locality in southern Nevada and California, 17,000 feet of Lower, Middle, and Upper Cambrian strata have been measured. This thickness gradually decreases northward through Utah to northern Idaho as the three divisions of the Cambrian successively overlap one another. A small positive area in northern Idaho and southernmost British Columbia separates the southern Cambrian trough from the northern. The positive area has been called the "Montana Island"[3] and "Montania."[4] In order to conform to a nomenclature adopted for the book of which this article is to be a chapter, the uplift will be called a "dome." It is the present site of exposure of the great Beltian series of Proterozoic age.

North of the dome a second deep trough existed, in which the three divisions of the Cambrian also occur. The total thickness of the Cambrian sediments there is about 17,000 feet. It is in these strata that Walcott made his famous studies of Cambrian life. Out of the strata are sculptured the high and scenic Canadian Rockies of the Banff and Jasper regions.

The Ordovician strata are fairly thick in both the southern (5,000 feet) and the northern (2,500 feet) divisions of the trough, but Silurian strata occur principally in the southern.

The distribution of the early Paleozoic strata is fairly well known westward to

[3] Schuchert, 1924 ed. of ftn. 1.

[4] C. F. Deiss, "Cambrian Geography and Sedimentation in the Central Cordilleran Region," *Bull. Geol. Soc. Amer.*, Vol. LII (1941), pp. 1085–1116.

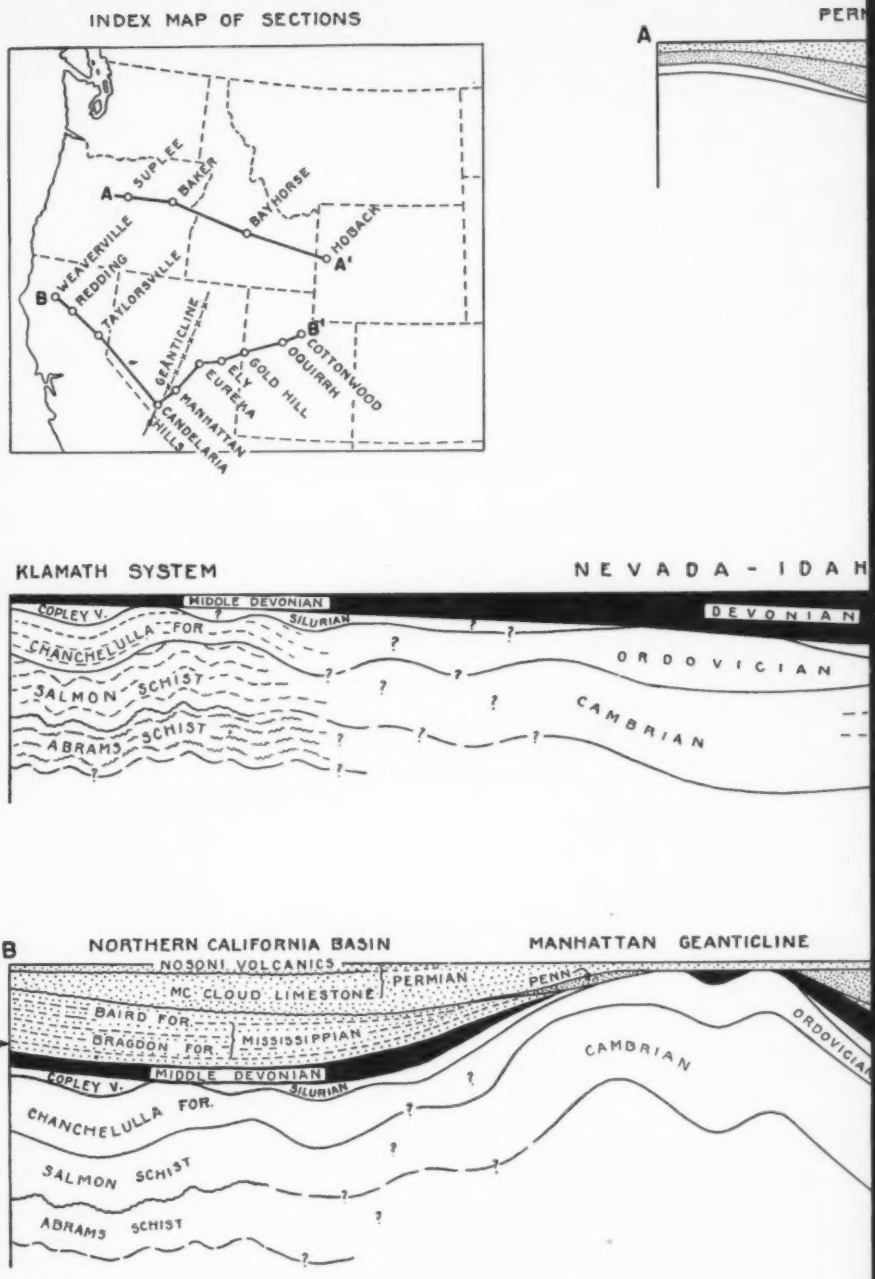
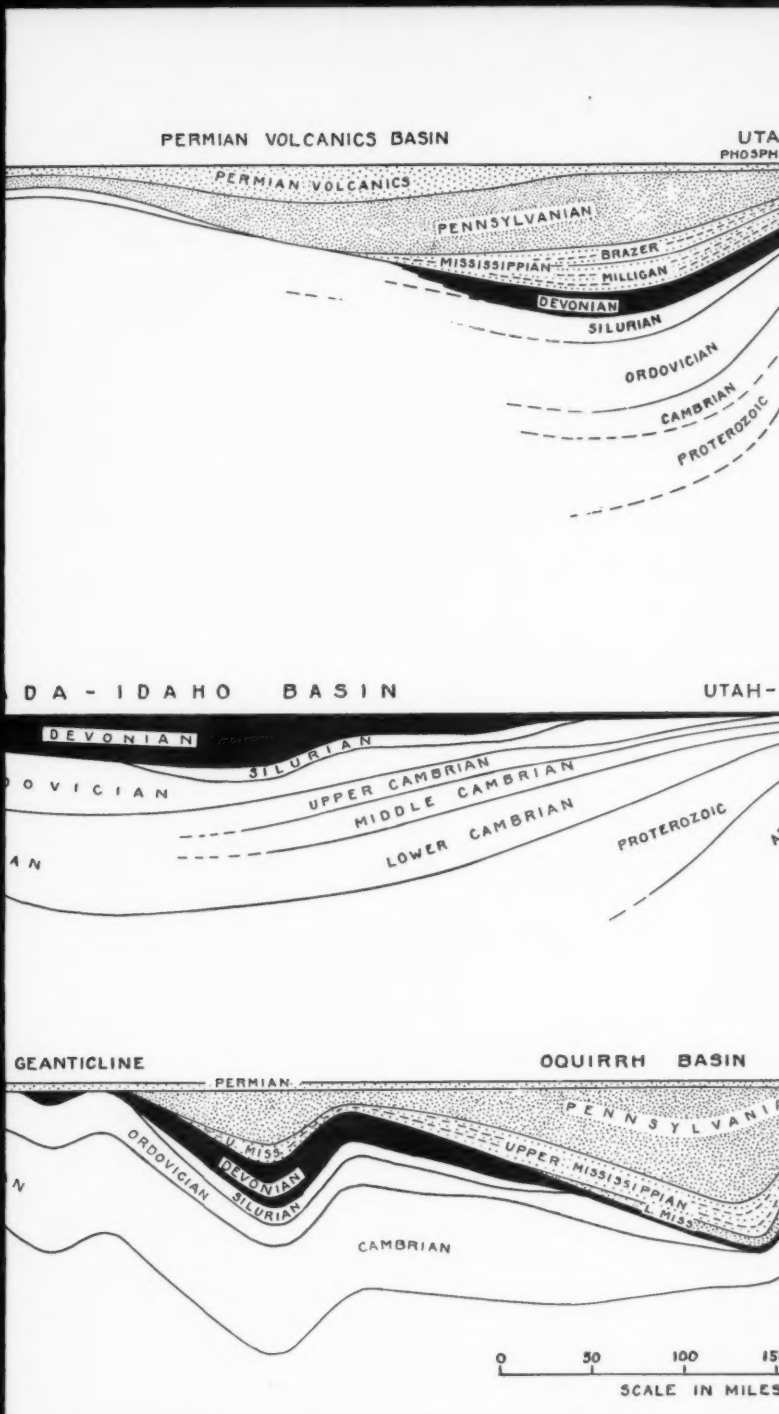
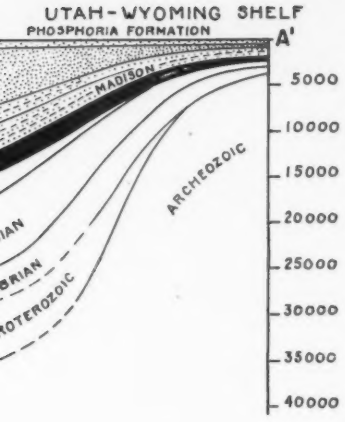
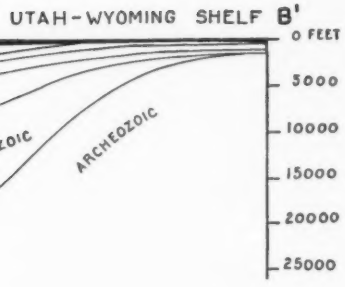


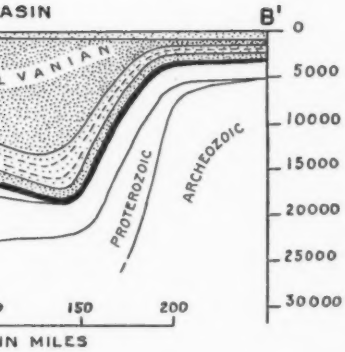
FIG. 3.—Sections to illustrate the Paleozoic basins at the close of the Devonian and at the close of the
ed to denote lithology but to render distinction and contrast to the systems. Section *B–B′* after Nolan (ftn



n and at the close of the Permian. Patterns for the Devonian, Mississippian, and Pennsylvania
on *B–B′* after Nolan (ftn. 5) and Hinds (ftn. 26).







nsylvanian rocks are not intend-

central Nevada in the southern trough,[5] but the lithology of the connecting link with the formations of the Pacific trough is largely unknown. This is due to the great Jurassic batholiths and the cover of Tertiary volcanics (examine cross sections of Fig. 3).

Although a trough in the site of the Canadian Rockies extending northward to the Mackenzie delta is postulated by several students of paleogeography, the western flank of the trough has not been located. C. D. Walcott's[6] sections in southern British Columbia were isopached for each division of the Cambrian and for the Ordovician, and then the four isopach maps were superposed and collectively contoured. The result showed a progressively deepening trough westward, with only the slightest indication of a trough axis before metamorphic rocks appear, which have been called "pre-Cambrian" (see Fig. 1). It is now fairly well demonstrated that the metamorphic rocks which spread to the Pacific trough are not only of pre-Cambrian age but also of Paleozoic age, and therefore it seems likely that sedimentation occurred from the northern Rocky Mountain trough to the Pacific trough. A slight swell may have separated the two; but, if it existed at all, it should be considered as a linear zone of the crust that failed to subside as rapidly as the troughs on each side.

Far north along the Mackenzie River in the Northwest Territories, 3,500–4,500 feet of pre-Devonian Paleozoic strata have been observed,[7] which are chiefly Silurian and Ordovician in age. They are in part an evaporite sequence. So little is known of their distribution that no attempt has been made to extend the isopachs of the northern Rocky Mountain trough to this region.

Devonian basin.—Although Devonian strata are found nearly everywhere west of the transcontinental arch, they are over 1,000 feet thick only in the western part of the general Rocky Mountain area (see Devonian map of Fig. 2). In the Roberts Range, Nevada, C. W. Merriam[8] has described 4,465 feet of Devonian beds, and at near-by Eureka he has found 4,000–5,000 feet of them. They are composed chiefly of limestones and dolomites, their fossil content indicates a rather complete section, and the broad trough in which they accumulated subsided during most of Devonian time.

Another fairly deep Devonian basin is known in the far north—the Norman Wells district on the Mackenzie River in the Northwest Territories.[9] A maximum thickness of 3,500 feet of Middle and Upper Devonian beds has been described; but, since they are at the surface over an extensive area northward to the Mackenzie delta or are overlapped southward by the Cretaceous, it appears that the original thickness may have been greater and was comparable to the thickness in the Nevada basin.

Mississippian basins.—The Lower Mississippian Basin, in which the Madison limestone and equivalents were deposited, is somewhat different from the

[5] T. B. Nolan, "The Basin and Range Province in Utah, Nevada, and California," *U.S. Geol. Surv. Prof. Paper 197-D* (1943), pp. 141–96.

[6] "Pre-Devonian Paleozoic Formations of the Cordilleran Provinces of Canada," *Smithsonian Misc. Coll.*, Vol. LXXV (1928), pp. 175–368.

[7] J. S. Stewart, "Petroleum Possibilities in Mackenzie River Valley, N.W.T.," *Trans. Can. Inst. Min. Met.*, Vol. XLVII (1944), pp. 152–71.

[8] "Devonian Stratigraphy and Paleontology of the Roberts Mountains Region, Nevada," *Geol. Soc. Amer. Special Paper 25* (1940), pp. 1–144.

[9] See ftn. 7.

Upper Mississippian Basin, in which the Brazer formation and equivalents accumulated, and therefore the Mississippian crustal movements will be treated in two stages (see Mississippian map of Fig. 2). The Madison Basin, as defined by the 1,000-foot-thickness contour, is limited to a gangling trough in southern Nevada, central Utah, eastern Idaho, and central Montana. The thickness of sediments is greatest near Pioche, Nevada, where L. G. Westgate and A. Knopf[10] record about 3,000 feet. They make up the Bristol Pass limestone and the Peers Spring formation. At Three Forks, Montana, 1,800 feet of beds have been measured[11] and, farther north in the Saypo quadrangle, 1,000 feet.[12] The suggested thinning northward toward the International Boundary is substantiated by the presence of nothing but Beltian (Proterozoic) rocks in the Glacier National Park area.

J. S. Williams[13] believes a landmass must have existed in northern Colorado and south-central Wyoming from which sandstones and various red beds were derived.

In the Death Valley region of California the Lower Mississippian beds are probably over 2,100 feet thick, and therefore it appears that the Madison trough extended southwestward through the Pioche district, where the Lower Mississippian is about 2,800 feet thick, to Death Valley. No thick Upper Mississippian section is known in the area of southern Nevada and northwestern Arizona.

Larger and deeper basins formed in Upper Mississippian time than in Lower. The Brazer Basin of northern Utah and southeastern Idaho is well known. J. S. Williams[14] has measured nearly 3,000 feet in Big Cottonwood Canyon, 1,750 feet in Weber Canyon, and 3,100 feet in Wellsville Mountain (all in the Wasatch Mountains); and G. R. Mansfield[15] lists over 1,100 feet in southeastern Idaho. In the Makay region of central Idaho, Umpleby *et al.*[16] state that the section may be much more than 6,000 feet thick. This great thickness corresponds with Nolan's 6,000 feet for the Woodman and Ochre Mountain formations of Gold Hill, Utah.

At Pioche, Nevada, the Upper Mississippian is represented probably by the Scotty Wash quartzite and by the lower half of the Bailey Spring limestone, and these beds are about 2,000 feet thick.

In the San Francisco District, Utah, the Topache limestone is probably Upper Mississippian and is 1,500 feet thick. No Lower Mississippian exists there.

The Lower Mississippian strata of Arizona do not exceed 300 feet in thickness.[17] Upper Mississippian are thin and occur only in the southeastern corner.

In the Muddy Mountains, Nevada,

[10] "Geology and Ore Deposits of the Pioche District, Nevada," *U.S. Geol. Surv. Prof. Paper 171* (1932).

[11] George W. Berry, "Stratigraphy and Structure at Three Forks, Montana," *Bull. Geol. Soc. Amer.*, Vol. LIV (1943), pp. 1–30.

[12] C. F. Deiss, "Stratigraphy and Structure of Southwest Saypo Quadrangle, Montana," *Bull. Geol. Soc. Amer.*, Vol. LIV (1943), pp. 205–62.

[13] "Carboniferous Formations of the Uinta and Northern Wasatch Mountains, Utah," *Bull. Geol. Soc. Amer.*, Vol. LIV (1943), pp. 591–624.

[14] *Ibid.*

[15] "Geography, Geology, and Mineral Resources of Part of Southeastern Idaho," *U.S. Geol. Surv. Prof. Paper 152* (1927), pp. 1–409.

[16] J. B. Umpleby, L. G. Westgate, and C. P. Ross, "Geology and Ore Deposits of the Wood River Region, Idaho," *U.S. Geol. Surv., Bull. 814* (1930).

[17] A. A. Stoyanow, "Correlation of Arizona Paleozoic Formations," *Bull. Geol. Soc. Amer.*, Vol. XLVII (1936), pp. 459–540; "Paleozoic Paleogeography of Arizona," *ibid.*, Vol. LIII (1942), pp. 1255–82.

Longwell estimates about 600 feet of Lower Mississippian and perhaps over 900 feet of Upper Mississippian.

In Upper Mississippian time a fairly pronounced basin developed in east-central Montana and western North Dakota, and in it the Big Snowy group was deposited. The beds attain a maximum thickness of about 1,500 feet.[18] It is not clear whether the sediments for the Big Snowy Basin came from a highland on the south or the north.

Manhattan geanticline.—Toward the end of the Devonian period, according to Nolan,[19] a geanticline began to rise in west-central Nevada, approximately along the line of maximum sedimentation of the early Paleozoic (see Figs. 2 and 3). The uplift divided the geosyncline into a western and an eastern trough, and the distribution of Devonian sediments is reflected in two ways, viz., by the almost complete removal of the earlier Devonian deposits along the axis of the arch and by an eastward shift to the vicinity of Eureka, Nevada, of the zone of maximum sedimentation. Since most other major structural features have been given names, it is desirable for the purpose of illustration on the tectonic maps to assign one to the geanticline in central Nevada. The axis of it runs approximately through Manhattan, where a good section has been measured; hence the name "Manhattan geanticline" seems appropriate.

The large proportion of clastics in the Mississippian and in the lower part of the Pennsylvanian sequences in California and the coarse material in the upper part of the Pennsylvanian at Eureka, Nevada, indicate that elevation of the geanticline continued and that it was subject to erosion throughout nearly all Mississippian and Pennsylvanian time.[20]

The Permian marked the close of the elevation and planation. Slight submergence probably permitted deposits of that period to be laid down over the entire area.

The elevation of the arch was accomplished by broad warping, but folding occurred locally, so that angular discordances up to 35° exist, such as in the Candelaria Hills–Miller Mountain area, where the underlying Ordovician strata are truncated by the Permian.

The axis of the geanticline has been traced as follows:[21] Near Austin, Nevada, Pennsylvanian limestone is reported to rest on slates and limy shales of probable Ordovician age. To the south the axis is drawn west of the Inyo Range because of the similarity of the section to that of Eureka and its difference from the Carboniferous Calaveras formation in California. What happened to the geanticline southward is unknown. It may have merged with a broad area of uplift or orogeny. The course of the geanticline west of the Inyo Range marks the site of greatest sediment accumulation in pre-Carboniferous time.

Still farther north the section in the Ruby Mountains[22] indicates that the axis of the upwarp is to the west. It is, therefore, headed toward the Bayhorse and Wood River regions of Idaho, but the thick sections there are typical of those of the undeformed basin, and hence the geanticline appears to have died out approximately at the Idaho line.

[18] H. W. Scott, "Some Carboniferous Stratigraphy in Montana and Northwestern Wyoming," *Jour. Geol.*, Vol. XLIII (1935), pp. 11–32; N. Ballard, "Regional Geology of Dakota Basin," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XXVI (1942), pp. 1557–84.

[19] See ftn. 5.

[20] *Ibid.*

[21] *Ibid.*

[22] R. P. Sharp, "Stratigraphy and Structure of the Southern Ruby Mountains, Nevada," *Bull. Geol. Soc. Amer.*, Vol. LIII (1942), pp. 647–90.

Pennsylvanian and Permian basins.—Pennsylvanian sediments are widespread in the western United States, and in places they attain great thicknesses. According to Nolan,[23] they show more abrupt changes in thickness within relatively short distances than do the Upper Mississippian sections; and this variability, together with the higher proportion of clastic material in the beds and the presence of local unconformities, indicates considerable instability of the broad geosynclinal area during Pennsylvanian time. The greater clastic content appears to be especially characteristic of the sedimentary sections near the eastern and southeastern borders of the province and suggests the presence in this region of marked crustal activity. The Ancestral Rockies may have furnished much of the sand (see Pennsylvanian map of Fig. 2).

The basin sank most in west-central Utah, where 18,000 feet of beds are recorded.[24] At several other near-by places 8,000–10,000 feet have been measured. The deep basin is approximately contoured on the map and is labeled the "Oquirrh Basin," from the Oquirrh Range, where the greatest thickness occurs.

Another fairly deep basin formed in southern Nevada and southern California, where a maximum of 7,750 feet of Pennsylvanian rocks are known.[25]

Pennsylvanian beds in western Nevada, northern California, Oregon, and Washington are dominantly volcanic and will be described under the next heading.

[23] See ftn. 5.

[24] James Gilluly, "Geology and Ore Deposits of the Stockton and Fairfield Quadrangles, Utah," *U.S. Geol. Surv. Prof. Paper 173* (1932).

[25] Adolph Knopf, "A Geologic Reconnaissance of the Inyo Range and the Eastern Slope of the Southern Sierra Nevada, California, with a Section on the Stratigraphy of the Inyo Range by Edwin Kirk," *U.S. Geol. Surv. Prof. Paper 110* (1918).

East of the Manhattan geanticline the strata are sandstones, shales, and limestones.

Permian sediments are very widespread in the western Cordillera and consist, in general, of two divisions: the eastern marine sequences and the western bedded volcanic series. The eastern trough is not large if marked off by the 1,000-foot isopach (see Permian map, Fig. 2); but in one place in central Utah it sank over 10,000 feet and was filled with marine limestone, shale, and sandstone beds. Over shallow shelves to the north, especially in northern Utah, eastern Idaho, western Wyoming, and south-central Montana, great quantities of chert and phosphatic limestone and shale were deposited.

PACIFIC TROUGH

In the Klamath Mountains.—The pre-Devonian rocks in the Klamaths are metamorphosed and, their age is a matter of guess. The section represented (Figs. 3 and 4) is that given by N. E. A. Hinds[26] for the southern Klamath Mountains in northern California, specifically in the Redding, Weaverville, and northwestern part of the Red Bluff quadrangles. Formations dated because of fossil content are of Devonian, Mississippian, and Permian age. Formations older than Middle Devonian, but in which no fossils have been found, are the Copley meta-andesite, the Chanchelulla formation, the Salmon schist, and the Abrams schist. The two schists have been called collectively the "Siskiyou terrane." Although the schists are separated from each other by an unconformity and are, therefore, of different ages, they form a distinct unit because they are equally

[26] "Paleozoic Section in the Southern Klamath Mountains, California," *Proc. 6th Pacific Sci. Cong.*, Vol. I (1939), pp. 273–88.

metamorphosed and much more so than the later formations of the area. They accumulated to a thickness of at least 5,000 feet in a trough that extended for a known distance of 200 miles north and south in northern California and southwestern Oregon. Pebbles and boulders of the Salmon and Abrams schists are found in conglomerates of the overlying Chanchelulla formation. Metamorphism, deformation, and deep erosion of the schists preceded the accumulation of the Chanchelulla, and therefore it is possible that the Salmon by an erosional unconformity[28] and is made up dominantly of mica schist, with mica quartz schist and metaquartzite present in places. It is the oldest rock known in the Klamath Mountains and may be pre-Cambrian, but a Cambrian age is certainly not excluded. It is estimated to be at least 5,000 feet thick.

The Chanchelulla formation overlies the schists "with moderate angular and distinct erosional unconformity"[29] and forms a broad belt which, as far as is

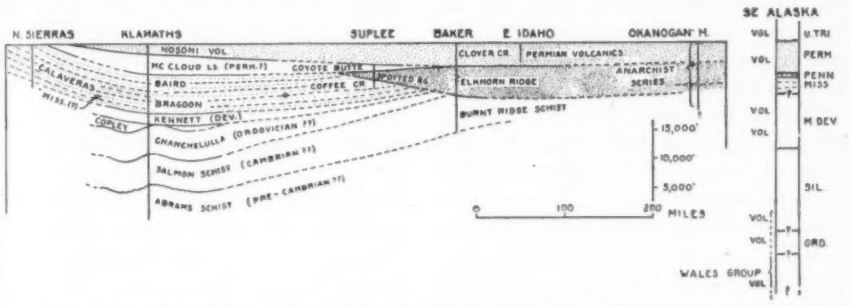


FIG. 4.—Possible correlation of the volcanics and metamorphic sequences of the Cordilleran geosyncline in northern California, Oregon, and Washington. The vertical lines indicate the extent of the exposed sections. The drawing is an attempt to restore the relations as they were before the post-Permian, pre-Triassic folding. "Vol" under "SE Alaska" indicates position of various volcanics in the systems.

they are much older. Hinds[27] believes that they are both pre-Silurian. In cross section *B–B′* of Figure 3 the Salmon schist is questionably shown to be Cambrian and the Abrams pre-Cambrian. The Salmon is composed of hornblende and chlorite schist and was originally a series mostly of fine, water-laid, basic volcanic-ash beds. Since most other Paleozoic formations in the Pacific trough contain much volcanic material, it seemed logical in drawing the cross section to correlate the Salmon with the Cambrian. It is purely an assumption, however.

The Abrams schist is separated from known, runs in a northwest direction. The base is composed largely of gray, thinly bedded, recrystallized chert. Interbedded are micaceous, graphitic, and calcareous schists, quartzite, metaconglomerate, and marble. Toward the top of the formation the proportion of mica schist, partially metamorphosed sandstone, conglomerate, and limestone is considerably greater. The strata have been strongly folded and moderately metamorphosed, though recrystallization is much less intense than in the underlying schists. The formation exceeds 5,000 feet in thickness.

After the sediments were deposited,

[27] *Ibid.*

[28] *Ibid.*

[29] *Ibid.*

they were invaded by sills of andesite and andesite prophyry, some 200–500 feet thick, with great areal extent. The andesites have since been metamorphosed to greenstone or chlorite schist. The meta-andesites closely resemble the overlying Copley volcanics, and their degree of metamorphism is similar. The suggestion is strong, therefore, that the basic rocks of the Chanchelulla formation are intrusive components of the Copley eruptives.

The Chanchelulla is pre-Copley, which is pre-Middle Devonian. Hinds believes the Chanchelulla is early Paleozoic, and it seems to correlate on the cross section conveniently with the Ordovician system farther east.

Widely distributed through the Klamath and Siskiyou Mountains are remnants of a great volcanic series called the "Copley meta-andesite." The formation consists of coarse and fine andesitic and basaltic pyroclastics, with interbedded flows of pyroxene, andesite, and basalt. Sections 1,500 feet thick have been measured, but good sections are hard to find, and the original thickness is not known.

The Copley volcanics have generally been metamorphosed to greenstone schists, but the intensity of recrystallization varies from place to place. Porphyritic flows, both vesicular and amygdaloidal, and brecciated, blocky, or clinkery lavas are not uncommon. Near the contacts of the Nevadan (late Jurassic) intrusions, the volcanics have been recrystallized generally to chlorite schist. The metamorphism by the granite intrusives has been superimposed on the earlier metamorphism.

The Copley volcanics lie with "pronounced angular and erosional discordance" upon the Siskiyou schists and the Chanchelulla formation and are overlain unconformably by the Middle Devonian Kennett formation. The Copley is shown related to the Silurian strata of the Taylorsville region, but this is simply a matter of necessity after the Chanchelulla was made equivalent to the Ordovician. J. S. Diller[30] has collected Silurian fossils from the oldest rocks found in the Taylorsville district, but these rocks are chiefly thin-bedded quartzite with dark slaty shale and limestone and do not resemble the Copley volcanics.

In Devonian time the western margin of the broad basin in Nevada was filled chiefly with black clays, now shales and slates. They are highly siliceous and contain thin beds of sandstone and lenses of fossiliferous limestone, now largely recrystallized. The Devonian beds are known as the "Kennett formation" and crop out in two rather restricted belts in the Klamath Mountains. No strata yet identified as Devonian are known in California south of the Klamaths in the Sierra Nevada Mountains or the Coast Ranges, and none have been noted in Oregon to the north.

The Kennett lies unconformably on the deformed and eroded Copley meta-andesite, and the basal strata of the Kennett contains rock fragments, evidently from the volcanics.[31]

The Devonian strata were originally thicker than now, having been subjected to erosion and entirely removed in places. As a consequence, the Mississippian beds rest directly on the Copley volcanics over large areas.

The Mississippian is made up of two formations in the Klamath Mountains—the Bragdon and the Baird. They are probably the most widespread formations in the region. The Bragdon is chief-

[30] "Geology of the Taylorsville Region, California," *U.S. Geol. Surv. Bull. 353* (190).

[31] See ftn. 26.

ly shale and slate, generally gray, in contrast to the black shale and slate of the older Kennett formation. Some sandstones are conglomeratic near the base and contain fragments of both the Kennett and the Copley formations. Within the Redding quadrangle a volcanic sequence, called the "Bass Mountain basalt," is present. The Bragdon may exceed 6,000 feet in thickness in places. The Bass Mountain volcanic sequence contains many tuff beds in places. Its position on Bass Mountain, according to Hinds, is in the lower part of the Bragdon formation.

The Baird formation consists largely of sandstone and tuff, but the upper part has calcareous and siliceous slates. It is about 700 feet thick and apparently rests conformably on the Bragdon.[32]

The McCloud limestone is a highly fossiliferous formation and was probably a massive cherty limestone, but now, because of the Jurassic intrusions, it is mostly metamorphosed in various degrees to marble. It reaches a maximum thickness of 2,000 feet. Its fossils were first thought to represent a Pennsylvanian age, but a recent study by Wheeler[33] shows them to be Lower Permian.

The McCloud limestone overlies the Mississippian Baird formation disconformably; hence it appears that most of the Pennsylvanian was a time of emergence.

The Nosoni formation is composed of basaltic agglomerates; lithic crystal tuffs; flows of andesite and of olivine basalt; dark brown, fossiliferous, shaly limestone; and dark-gray to brown tuffaceous shales and slates. The maximum thickness measured by Hinds is 1,200 feet. It is considered to be upper Lower Permian.[34] Hinds[35] believes that the Nosoni volcanics rest on an erosion surface on the McCloud limestone.

In the Sierra Nevada Mountains.—In the northern Sierra Nevadas a metamorphic formation of Carboniferous age is widespread and consists chiefly of black phyllite, with subordinate fine-grained quartzite, limestone, and chert. It is known as the "Calaveras formation." Associated and in part interbedded with the formation are green amphibolite schists of contemporaneous age. From fossils, found chiefly in the limestone, the Calaveras formation is known to be, in part at least, of Carboniferous age, but parts of it as mapped may be Devonian and Triassic. Because of the metamorphosed condition of the rocks in which the fossils are found, it has been difficult for paleontologists to determine to what part of the Carboniferous the faunas belong. Girty[36] thought groups of Calaveras fossils from the Taylorsville region are more closely related to the Baird, now recognized as Mississippian, than to the McCloud limestone, now believed to be Permian. The amphibolite schists were originally fine pyroclastics.[37]

The bedded rocks are most abundant in the northern Sierras, but southward they become increasingly metamorphosed, and progressively greater areas are occupied by granitic intrusives. In the Tehachapi Mountains and the southern Coast Ranges, pregranitic rocks are present, but highly altered, and their ages are speculative.

[32] *Ibid.*

[33] *Ibid.*

[34] H. E. Wheeler, "Fusulinids of the McCloud and Nosoni Formations of North California," *Bull. Geog. Soc. Amer.*, Vol. XLIV (1933), p. 218.

[35] See ftn. 26.

[36] See ftn. 30.

[37] Adolph Knopf, "The Mother Lode System of California," *U.S. Geol. Surv. Prof. Paper 157* (1929).

In central Oregon.—A heterogeneous group of east–west-trending ranges and dissected lava plateaus, known collectively as the "Blue Mountains uplift" or the "Blue Mountains–Ochoco Mountains uplift,"[38] extends from central to eastern Oregon. The ranges are formed of Paleozoic and Mesozoic sediments and lavas and Mesozoic plutons, and the complex protrudes island-fashion through the Columbia River lava fields. The oldest beds that crop out are Lower Carboniferous limestones and calcareous sandstones[39] (see Figs. 4 and 5). About 1,000 feet of them are exposed, and they are called the "Coffee Creek formation." No volcanic materials have been noted.

Overlying the Coffee Creek formation is the Spotted Ridge formation. The exact contact relations have not been observed, but, if an unconformity does exist, it is probably not angular and does not represent much of a time break. The Spotted Ridge consists of plant-bearing sandstones and mudstones; conglomerates containing diorite, andesite, and dacite boulders; and bedded chert. It may be 1,500 feet thick. The plants are believed to be Lower Pennsylvanian.

The Coffee Creek and Spotted Ridge formations are reported as intensely folded, but no mention is made of metamorphism.[40] They lie in a tectonic belt of deformed strata in which the rocks on the west (Klamaths) and on the east (Baker area) are metamorphosed, and it is puzzling that they also are not metamorphosed.

[38] A. C. Waters, "Summary of the Sedimentary, Tectonic, Igneous, and Metalliferous Geology of Washington and Oregon, Ore Deposits of the Western United States," *Lindgen Volume, A.I.M.E.* (1933), pp. 253–65.

[39] C. W. Merriam and S. A. Berthiaume, "Late Paleozoic of Central Oregon," *Bull. Geol. Soc. Amer.*, Vol. LIV (1943), pp. 145–72.

[40] *Ibid.*

The Spotted Ridge is overlain by the Coyote Butte formation. A slight angular unconformity separates the two. The Coyote Butte is composed almost entirely of massive limestones. Some chert pebble conglomerates are present near the base. The age is probably Lower Permian.

A prominent angular unconformity exists between the Paleozoic beds of central Oregon and the overlying Triassic conglomerates, which attain a thickness of 4,000 feet.

In eastern Oregon.—In the Baker quadrangle of eastern Oregon, James Gilluly[41] described a formation—the Burnt River schist—which, chiefly because of greater metamorphism than that of known Carboniferous rocks near by, he cautiously treats as older. The rock varieties are greenstone schist, quartz schist, conglomerate schist, limestone, slate, and quartzite, and they make up a series at least 5,000 feet thick, perhaps several times as much. The various types mentioned grade into one another.

Gilluly visualizes the origin of the strata as follows:

> . . . . pyroclastic material was added in amounts varying from time to time to a basin of sedimentation to which at some times sand and at others clay, with some carbonates, were being supplied. When volcanic contributions were small the deposits were such as have yielded the quartzites and carbonaceous slates now found, but when the volcanic material increased relative to the normal terrigenous sediment the deposits were such as have yielded the intermediate rocks. . . . . At times such floods of volcanic material were contributed that practically unmixed tuff was formed.

The Burnt River schist has lithologic similarities with the Calaveras formation but differs, it seems, in generally having

[41] "Geology and Mineral Resources of the Baker Quadrangle, Oregon," *U.S. Geol. Surv. Bull. 879* (1937).

GRINDSTONE-TWELVEMILE CREEKS AREA, CENTRAL OREGON (MERRIAM AND BERTHIAUME)

Cc, Coffee Creek fm. (Lower Carb.) Cs, Spotted Ridge fm (Penn.) Pc, Coyote Butte fm. (Perm.)

1 MILE

NORTH-SOUTH SECTION NEAR BAKER, OREGON (GILLULY)

brs, Burnt River schist; Ce, Elkhorn Ridge argillite (Penn.?) Ccg, Clover Creek greenstone (Perm.)

qd, biotite-quartz diorite; sg, silicified gabbro; mg, metagabbro; gb, gabbro

5 MILES

FIG. 5.—Cross sections in central and eastern Oregon

greater metamorphism and an absence of chert. The Burnt River appears from published descriptions to be surprisingly similar to the Salmon schist of the Klamaths, which is probably pre-Silurian (see Figs. 4 and 5).

Above the Burnt River schist is the Elkhorn Ridge argillite, about 5,000 feet thick. It is probably the most widespread of the pre-Tertiary formations and is a thick series of argillite, tuff, and chert with subordinate limestone and greenstone masses. A number of large intrusive bodies have been noted in the east-west belt of argillite; and these, together with the overlapping Cenozoic rocks, effectively prevent the recognition of contacts and the determination of stratigraphic relationships. The beds are Pennsylvanian in age because of fusulinid fossils found in the limestones. Beds younger than Pennsylvanian may have been included in the formation as mapped.[42]

The whole formation is provisionally considered marine. The tuffaceous argillite, the tuff, and the tuffaceous limestone all clearly attest notable pyroclastic contributions to the formation, and it is highly probable that cherts as numerous and thick as those in this formation may be considered evidence of igneous contribution also.

The association of limestone with volcanic materials may have no genetic significance, but a dependency is suspected because volcanism might have raised the temperature of the sea and hence decreased the solubility of the lime.[43]

The Clover Creek greenstone overlies the Elkridge argillite and consists of altered volcanic flows and pyroclastic rocks, with subordinate conglomerate, limestone, chert, and argillite. It is known to extend as far eastward as the Snake River Canyon and is therefore probably the same as the "Permian volcanics" of several areas in eastern Idaho. It is at least 4,000 feet thick.[44]

The effusive rocks in order of abundance are quartz keratophyre (lava-bearing albite), quartz keratophyre tuff, and meta-andesite. Fossils collected from the formation betray a Permian age.

The marine limestone and associated fossiliferous tuffs demonstrate a marine origin for at least part of the formation. The type of albitization which most of the volcanic rocks have undergone is common in demonstrably submarine volcanic rocks, and the association here with marine limestone suggests rather strongly that the Clover Creek greenstone is, in large part, of submarine origin.

In central Idaho and northwestern Nevada.—During Permian time the volcanic rocks of the Pacific trough spread eastward an unusual distance to central Idaho and northwestern Nevada. The sequence is 5,000 feet deep at Blairsden in the Sierra Nevadas and thickens eastward to 12,000 feet in the Humboldt Range, Nevada.[45] Northwestward into central Idaho it thins to about 4,000 feet (see map, Fig. 2).

In northern Washington and southern British Columbia.—Where the Okanogan River crosses the International Boundary, extensive areas of pre-Tertiary rocks are found. The pre-intrusive (pre-Jurassic) metamorphic rocks are called the "Anarchist series" and crop out in the Okanogan Range adjacent to the Okanogan Valley on the west and extensively in the Okanogan Highlands on the east.

[42] *Ibid.*

[43] *Ibid.*

[44] *Ibid.*

[45] See ftn. 5.

According to D. B. Krauskopf,[46] neither the top nor the bottom of the Anarchist series has been found, but at least 10,000 feet of beds exist. They can be divided rather vaguely into three divisions: the lower consists chiefly of gray to jet-black phyllites, with some interbedded quartzite and a little chlorite schist; the middle consists of limestone, massive quartzite, graywacke, conglomerate, some phyllite, and, to the north and east, much greenstone; the upper consists, for the most part, of greenstone, with some interbedded phyllite and quartzite. The albite in the greenstones of the upper division suggests a correlation with the keratophyres of eastern Oregon.

Regional metamorphism has converted the original sedimentary and volcanic rocks to a typical chlorite-zone assemblage. Near some of the plutonic bodies higher-grade contact metamorphism has been superimposed, yielding biotite and amphibolite schists and diopside rocks.[47]

A few fossils establish a marine origin for part of the series at least and a late Paleozoic age.

In Stevens County of northeastern Washington, C. E. Weaver[48] described the Stevens series, a group of metamorphic rocks with the great thickness, reportedly of 42,900 feet. It consists of quartzites, argillites, phyllites, dolomitic limestones, and schists. It is believed to be in part of Carboniferous age, but the lower parts are probably older. H. Bancroft[49] had previously found fragmentary plant fossils, which appeared to be Carboniferous.

The Carboniferous part of the Stevens series is probably equivalent to part of the Anarchist series on the west and to the Pend Oreille group[50] on the northeast along the forty-ninth parallel. The Pend Oreille is also considered to be in part Carboniferous. It and equivalents rest on the immensely thick Beltian strata of Proterozoic age which form a north-south belt in northern Idaho, western Montana, and British Columbia east of Kootenai Lake.

In the Okanogan Valley of British Columbia, C. E. Cairnes[51] recognizes a thick series of metamorphosed sediments, chiefly argillaceous—the Nisconlith series—and an overlying group of mixed volcanic and sedimentary rocks, which are fossiliferous in places and of late Carboniferous or Permian age—the Cache Creek group. The Nisconlith has been classed as both Paleozoic, Beltian, and pre-Beltian; but its age, other than pre–Cache Creek, is not known, because no fossils have been found in it.

Just north of the International Boundary in the Okanogan Valley (map 538*A*, Canada Dept. Mines and Resources) the Kobau group has been described. It is composed of much altered sediments and volcanic rocks. The sediments appear to have been originally argillaceous, and the amphibolitic and chloritic schists appear to have been andesitic lavas. Some Permian fossils have been found in limestone beds that appear to overlie the Kobau beds conformably, and hence the

[46] "Pre-Tertiary Intrusives of the Okanogan Valley (Washington) near the Forty-ninth Parallel," *Proc. 6th Pacific Sci. Cong.*, Vol. I (1939), pp. 223–29.

[47] *Ibid.*

[48] "The Mineral Resources of Stevens County," *Washington Geol. Surv. Bull. 20* (1920).

[49] "The Ore Deposits of Northeastern Washington," *U.S. Geol. Surv. Bull. 550* (1914), pp. 1–215.

[50] R. A. Daly, "Geology of the North American Cordillera at the 49th Parallel, Part II," *Can. Geol. Surv. Mem. No. 38* (Ottawa, 1912).

[51] "The Shuswap Rocks of Southern British Columbia," *Proc. 6th Pacific Sci. Cong.*, Vol. I (1939), pp. 259–72.

Kobau is regarded tentatively as Carboniferous.

In southwestern British Columbia, other Carboniferous series have been described, such as the Hozameen group and the Chilliwack group (map 737*A*, Canada Dept. Mines and Resources). The Hozameen is principally an intimate association of andesitic lavas (greenstone) and ribbon chert with argillaceous partings. No fossils have been found in it, but the rocks are similar to much of the widespread Cache Creek series, from which a number of collections of Permian fossils have been made in recent years. The Hozameen beds are probably somewhat younger than those of the Chilliwack group as exposed along the International Boundary. This series is predominantly sedimentary and has yielded marine Upper Carboniferous fossils.

Black slates, cherts, and limestones of Ordovician age occur in the northern Cascade Mountains,[52] as well as Carboniferous rocks equivalent to the Cache Creek group. Devonian rocks have been described west of the Cascades on the San Juan Islands.

Though major parts of the large area just described in northern Washington and southern British Columbia are underlain by highly metamorphosed crystalline rocks, they can no longer be regarded as entirely "Archean" or pre-Cambrian. Cairnes[53] and others have rather conclusively established their origin as metamorphic associations of the great Jurassic batholiths and their present state of metamorphism as no indication of the time when they were deposited. The formations mentioned above give a fragmentary conception of the nature of the accumulations in the Cordilleran geosyncline in this region in pre-Mesozoic time. Evidence and opinion seem to be growing to shape the conclusion that a large part of the Paleozoic rocks were deposited in Carboniferous time and that the Permian especially was a time of widespread volcanic accumulations.

A point of interest is the association, practically everywhere in the areas mentioned, of the Jurassic intrusions and the Carboniferous volcanics. The coincidence of the belt of intrusions and the earlier volcanic accumulations is shown on the map of Figure 6.

In southeastern Alaska.—The Paleozoic rocks in southeastern Alaska from latitude 54°30′ to 60° N. are of geosynclinal thickness and constitute a number of formations of Ordovician, Silurian, Devonian, Mississippian, Pennsylvanian, and Permian ages.[54] The stratigraphic succession is given in Table 1.

One of the commonest types of rock is andesite in various forms. It occurs in at least seven formations from Permian to Ordovician age, and perhaps older. Many of the volcanic rocks are now greenstone schist. Pillow lava is abundant in the Lower and Middle Ordovician, Silurian, Middle and Upper Devonian, Lower Permian, and Upper Triassic.

The other predominant rock types are sheared graywacke, slate, and phyllite. The vast amount of greenish graywacke with associated slate is the most striking feature of the stratigraphic sequence of southeastern Alaska. Graywacke is found in every system of the Paleozoic and Mesozoic, and in many places it is diffi-

[52] W. S. Smith, "Stratigraphy of the Skykomish Basin, Washington," *Jour. Geol.*, Vol. XXIV (1916), pp. 559–82.

[53] See ftn. 51.

[54] A. F. Buddington, and T. Chapin, "Geology and Mineral Deposits of Southeastern Alaska," *U.S. Geol. Surv. Bull. 800* (1929).

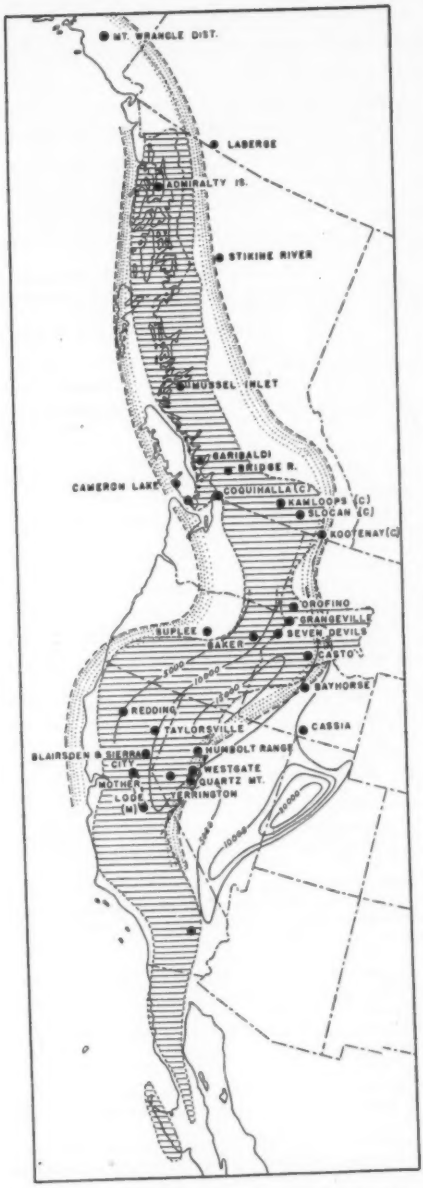


FIG. 6.—Map showing coincidence of Permian volcanic trough (*stippled margins*) and zone of Nevadan intrusives (*lined*). Dots indicate location of Carboniferous, Permian, and Triassic areas referred to in the text. Pennsylvanian and Permian basins combined isopached. Zone of Nevadan intrusives includes nearly all satellites and palingenetic areas.

TABLE 1

Series	Character	Thickness (Feet)
Jurassic		
	—Unconformity—	
Upper Triassic	Andesitic rocks, including breccia with limestone matrix and lava flows (in part with pillow structure), locally interbedded with slate and other sediments	1,400+
	—Unconformity—	
	Conglomerate, sandstone, and limestone; in the Ketchikan district includes considerable black slate in upper part	1,600±
	—Unconformity—	
Permian	Thick-bedded limestone: with common to abundant intercalated layers of white chert	1,000
	Conglomerate, limestone, sandstone, andesitic and basaltic lava, tuff, and, locally, rhyolitic volcanic rocks	3,000±
	—Unconformity—	
Pennsylvanian(?)	White massive limestone	100+
Mississippian	Interbedded coarsely crystalline limestone and black chert, overlain by interlayered dense gray quartzite and cherty limestone; sparse conglomerate	1,000
Upper Devonian	Basalt, andesite (in part pillow lava), tuff, limestone, sandstone, slate, and conglomerate	1,000
	—Unconformity(?)—	
	Limestone	600+
Middle Devonian	Andesitic green to gray tuff (locally cherty) and graywacke, with, locally, fine conglomeratic layers, intercalated limestone, and a minor amount of andesitic lava and breccia	2,400+
	Andesitic lava (in part pillow lava), breccia, tuff, conglomerate, and, locally, rhyolitic lava	2,000
	Interbedded limestone, slate, chert, andesitic lava, breccia, tuff, and, locally, conglomerate	?
	Conglomerate and graywacke-like sandstone, with, locally, interbedded limestone	2,000
	—Unconformity—	
Silurian	Green-gray graywacke with sparse conglomerate beds; interbedded red, green-gray, and gray graywacke-like sandstone, with a small amount of shale	5,000+
	Green-gray shale with intercalated red beds and thin-layered fine-grained gray sandstone, shale, and dense limestone	500+
	Predominantly thick-bedded dense limestone; intercalated with thick beds of coarse conglomerate, thin-layered limestone, nodular and shaly argillaceous limestone, and sandstone; limestone, 3,000± feet; conglomerate, 1,500 feet	4,500±
	Andesite (in part pillow lava) and andesite porphyry lava; conglomerate; with some associated graywacke, tuff, breccia, and limestone	3,000±
	—Unconformity(?)—	
	Indurated graywacke with associated black slate and sparse conglomerate and limy sediments	?
	—Unconformity(?)—	
Middle Ordovician	Indurated graywacke with associated black slate and sparse conglomerate and limy beds; locally, andesitic pillow lava and other volcanic rocks	?
Lower Ordovician	Thin-layered black chert with black graptolitic slate partings, graywacke, and, locally, andesitic volcanic rocks	?
Probably pre-Ordovician to Devonian Wales group (metamorphic rocks)	Greenstone schist with intercalated or interbedded limestone Limestone Schist with beds of limestone and slate Schist	?

After Buddington and Chapin (ftn. 54)

cult or impossible to tell one graywacke unit from another.

Limestone forms a very considerable part of each Paleozoic formation except the Ordovician. The thickest unit is in the Upper Silurian and is a very high-calcite variety. Some limestone carries considerable chert.

Beds of cobble and boulder conglomerate form conspicuous and thick members of the Silurian and Devonian formations. A peculiar, but common, form is composed of andesite and limestone pebbles and cobbles in a tuffaceous matrix. The same lithology is found in the Middle Devonian. Coarse conglomerate beds occur at the base of the Devonian.

Another characteristic lithology in the Paleozoic systems in southeastern Alaska is coarse, waterworn, intra-formational limestone conglomerate. Beds occur in the Silurian, Devonian, Permian, and Triassic formations; and in all of them the cobbles of limestone carry the same fauna as the formation in which the conglomerate occurs. Buddington believes the intra-formational conglomerates originated from crustal movements accompanying the volcanic activity during these periods.

Black slate and argillite are widely distributed, and thin-layered black chert, several hundred feet thick, occurs in the Ordovician and Mississippian formations. Thick-bedded chert and cherty tuff occur in the Middle Devonian, and white chert is common in the Upper Permian.

Schists and gneisses are also common and are the result principally of permeating hot solutions attendant upon the emplacement and solidification of the vast volume of magma, in addition to orogenic stresses.

In northern British Columbia and the Yukon.—The new geologic map of the Dominion of Canada (1946) summarizes what is known of the distribution of Paleozoic rocks in northern British Columbia and the Yukon. Great areas are still marked "Paleozoic, mainly sedimentary rocks," but other large areas are labeled "Carboniferous and Permian sedimentary and volcanic rocks." A report on the Cassiar Mountains, in the Finlay River district between latitudes 56 and 58 and longitudes 124 and 126, by Victor Dolmage,[55] describes a series of metamorphosed rocks of Carboniferous age. They are "green ash rocks pressed and altered into schists, interbedded with layers of graywacke, felsite, hälle-flinta, serpentine, and argillite." Along Takla and Stuart lakes and vicinity the series is made up of limestones, argillites, cherty quartzites, green schists, slates, volcanic flows, tuffs and breccias, and narrow bands of dolomite. *Fusulina* and other Carboniferous fossils have been found in some of these beds.

Underlying the Carboniferous series, great belts of schist and quartzite occur. Quartz mica schist constitutes about three-fourths of the whole. In many places the schist grades into quartzite, both of which were derived undoubtedly from siliceous sediments.[56] Such rocks as these are widespread and have been correlated with the Shuswap terrane of southern British Columbia, which now, as previously explained, is believed to be made up of rocks of several Paleozoic periods as well as pre-Cambrian. Also some coarse quartzites, quartz-pebble conglomerates, and limestones have been likened to the Cambrian strata of the southern Canadian Rockies, previously described.

The areas of such rocks are shown on

[55] "Finlay River District, B.C.," *Can. Geol. Surv. Sum. Rept.* (1927), Part A, pp. 19–41.

[56] *Ibid.*

the map of Figure 1. A great medial area of Proterozoic (Beltian?) rocks separates the western areas of Carboniferous rocks from the eastern Paleozoic rocks, but whether this was a highland in Paleozoic time or not is unknown. The relation of the Rocky Mountain trough to the Pacific, if at all distinct and separate, is not known in this far-northern Cordillera.

EVIDENCE OF PALEOZOIC OROGENY IN THE PACIFIC TROUGH

KLAMATH DIVISION

Extent.—In the Klamath division are included the late Paleozoic structures of the northern Sierra Nevada Mountains, the Klamath Mountains of northern California and southwestern Oregon, and the Ochoco and Blue mountains of central and eastern Oregon. These parts of the Klamath division were once connected but now are separated by extensive covers of later strata. The volcanics and most of the other clastics could have come only from the west, and it seems that the orogenic belt that supported some of the volcanoes and east of which submarine volcanic flows occurred must have lain a short distance west of the present exposures. The Klamath division was probably continuous with the Okanogan division on the north, from which it is now separated by the extensive Tertiary Columbia Plateau lavas.

Pre–Middle Devonian phase.—Evidence of crustal deformation in the Klamath system in upper Paleozoic time is the angular unconformity between the Copley meta-andesite and the Middle Devonian Kennett formation. The deformation was sufficient to fold the Copley and pre-Copley beds and to result in a landmass that was considerably eroded.

Since the overlying Kennett consisted originally of black clays for the most part, it is evident that the disturbance that resulted in the unconformity preceded the deposition of the fine clastics sufficiently to allow time for considerable erosion and for gentle submergence. Upon submergence of the Klamath area, the western landmass from which the sediments were derived must have been low lying or rather distantly removed, with a sea to the east, on the floor of which the black clays were deposited.

The disturbance is manifest in a gentle form several hundred miles to the east in the Nevada-Idaho Basin where, in the vicinity of the Manhattan geanticline (see Fig. 3, sec. B–B'), the Devonian rests on Ordovician. The Devonian Basin sank to its deepest extent in the central Nevada area and received chiefly lime sediments, as would be expected with a western landmass and an intermediate zone of accumulation of clastics.

The Copley andesites were slightly metamorphosed before the Jurassic intrusions superimposed local alterations; but whether the primary metamorphism was a result of the pre–Middle Devonian disturbance or others that followed in Carboniferous and Triassic time is not yet known. Hinds[57] points out that the degree of regional metamorphism on the Abrams and Salmon schists is considerably greater than that on the overlying strongly folded Chanchelulla and that an angular unconformity exists between them. If this relation is regionally true, it cannot be denied that a fairly intense orogenic disturbance separated the two formations. Regarding the post-Chanchelulla formations, however, it appears evident that geologists working in the Klamaths have not distinguished any special difference in degree of the original

[57] See ftn. 26.

dynamic metamorphism. The Copley meta-andesites, and the Kennett slates have about the same amount of metamorphism.

Late Devonian–early Mississippian phase.—Since the Bragdon formation of Mississippian age rests on both the Kennett and the Copley formations, it appears that the crust was restless again in late Devonian or early Mississippian time. The Bragdon was originally mostly clay, like the underlying Kennett, and it follows that the source of the sediments was a landmass, either low lying or distant, and that disturbance and erosion preceded the deposition of the Bragdon clays by some time.

The Bass Mountain basalt is the third episode of volcanism recorded to date in the Klamath system. The extrusion of lavas and tuffs on a large scale followed the pre-Mississippian disturbance and probably indicates continued crustal movements to the west.

Pennsylvanian phase.—In the Klamath Mountains the Lower Permian strata rest on the Mississippian if the latest age determinations are correct, and therefore the area was above water and suffered erosion during Pennsylvanian time. The uplift seemed more vigorous, yet the landmass was shorter lived, in the nearby Ochoco Mountains because Pennsylvanian beds there were deposited unconformably on older beds. Near Baker in eastern Oregon the Pennsylvanian argillites probably rest on the Burnt Ridge schist, which seems to be considerably older.

During most of the time that the Elkhorn Ridge (Pennsylvanian) was being deposited, much volcanic activity was occurring on the west, and pyroclastic contributions to the subsiding Pennsylvanian basin were intermittent but abundant.

In the Suplee district of central Oregon a slight angular unconformity separates the Pennsylvanian strata from the lower Permian, and therefore in places it seems that movements continued to the close of the Pennsylvanian.

Permian phase.—The Permian volcanics, which are so widespread in the great Cordilleran geosyncline, indicate that a fringe of volcanoes lay to the west, with submarine flows in the belt of present exposures and, unquestionably, that orogenic movements created either sizable landmasses or island archipelagos. The extensive Permian volcanism, together with the inferred crustal movements, is the first part of the Permian phase. Volcanism continued energetically in places into Triassic time, but in the Suplee district of Oregon an angular unconformity has been recognized between the Permian and the Triassic volcanic series. Compression in pre-Triassic time resulted in a series of folds striking northeast and north-northeast. Dips of 60° and more indicate that the folds were close and the deformation intense.[58] The cross sections (Fig. 5) show these folds in the Carboniferous and Permian strata, as well as the unconformity between them and the Triassic volcanics. The syncline of the Triassic beds strikes about N. 30° W. at the south end of its exposure and veers more northerly at its north end. The dips of the Triassic beds are greater than 40° in a number of exposures, but generally the folds seem more open than those of the beds below the unconformity. The episode of compression that folded the Triassic beds may be related to the late Jurassic Nevadan orogeny, or it may predate this event. Evidence is not at hand to make accurate dating possible.

[58] See ftn. 39.

In the Baker area, folding has been intense in all three formations exposed. The trends are westerly, the dips steep, folding probably isoclinal, and metamorphism dominant. Unfortunately, the critical lines of contact are obliterated by intrusions or masked by overlying Tertiary rocks, and, as the Burnt River schist is of uncertain age, it is impossible to work out satisfactorily the structural relations.[59] On the supposition that the Burnt River schist is pre-Carboniferous, the structure may be that of the north limb of a large anticlinorium, or possibly the schist may be overthrust on the Elkhorn Ridge argillite. It is also possible, in view of the notable shearing that all the rocks have undergone, that the Elkhorn Ridge argillite is thrust northward on the Clover Creek greenstone.

All the pre-Tertiary rocks except the youngest and most voluminous type of the intrusive bodies—the biotite-quartz diorite—have been subjected to thorough dynamic metamorphism. All have undergone shearing of the most pervasive sort and, concomitantly, have suffered mineralogic transformations. The metamorphism induced by the igneous intrusions has been slight. The Permian greenstones have been altered, where invaded, to hornfels or garnet gneiss, the Elkhorn Ridge argillite to spotted andalusite hornfels, and the Burnt River schist to amphibolite.[60]

The age of the dynamic metamorphism is the subject of greatest interest at this point. Is it post-Permian and pre-Triassic, late Triassic, or early Jurassic?

A group of basic intrusions in the Baker quadrangle are all believed to be magmatically related and hence of a single intrusive cycle. They are all affected equally by the dynamic metamorphism. Intrusive rocks, mentioned as basic plutonics, were intruded into Upper Triassic sedimentaries in the Ochoco Range and were exposed by erosion before being covered by the Lower Jurassic strata.[61] The basic plutonics have been altered to serpentine. If the serpentinization that Lupher mentions is of dynamic origin, as it might be,[62] then it would appear to be related to the metamorphism in the Baker quadrangle, and the general metamorphism of the prediorite rocks would be of late Triassic age. At least it seems safe to conclude that the folding, thrusting(?), and metamorphism is of post–early Permian and pre–early Jurassic time.

Writing about the Calaveras in the Mother Lode area, Knopf[63] states that the metamorphism that affected the formation differs markedly from that which altered the associated, but much younger, Upper Jurassic Mariposa rocks. He concludes that the metamorphism of the Calaveras took place at an earlier time and under other conditions than those that prevailed during the crustal folding in late Jurassic time. He believes that this pre-Mariposa metamorphism was a result of dynamic crustal compression. At the time that the Calaveras was being metamorphosed, or shortly afterward, considerable masses of diorite were intruded. The diorite is now, for the most part, schistose or gneissic, as a result of cataclastic deformation.

Spatial and time aspects of the orogenic belt.—The evidence summarized on the past several pages regarding the Paleo-

[59] See ftn. 41.

[60] *Ibid.*

[61] R. L. Lupher, "Jurassic Stratigraphy of Central Oregon," *Proc. Geol. Soc. Amer.*, Vol. LII (1941), pp. 219–70.

[62] L. V. Pirsson and Adolph Knopf, *Rocks and Rock Minerals* (2d ed.; New York: John Wiley & Sons, 1926).

[63] See ftn. 37.

zoic Cordilleran geosyncline and the Klamath division points to the following conclusions. A western belt of volcanoes contributed prominently to the accumulations in a flanking trough on the east. At certain times of little or no volcanic activity the land areas were low or distant. Crustal unrest was manifest from time to time in the volcanic belt, and the zone of disturbance extended eastward into the geosynclinal area sufficiently to cause unconformities between the sedimentary series. Not until late Permian or Triassic time, however, did intense orogeny pervade the Cordilleran geosyncline and cause the folding and metamorphism that are found in the Klamath division.

The different trends of the pre-Triassic and post-Triassic folds in the Suplee district and the still different strike of the beds in the Baker district may be due to orogenies of different times whose structures were discordantly superposed on one another. Also, as will be seen later, the Oregon part of the Klamath division and the Okanogan division, next to be discussed, are at the intersection of two great arcs of the general Paleozoic volcanic and orogenic belt, and in this area of intersection the structural trends would undoubtedly be complex. It is certainly the area in which the Nevadan batholiths are most irregular and complex and extend farthest eastward (see maps, Figs. 1 and 6). The palingenetic processes also were by far the most extensive at this area of intersection.

OKANOGAN DIVISION

The Okanogan division of the Pacific trough designates the Paleozoic structures in Washington and southern British Columbia. The areas of outcrop have already been listed. According to Krauskopf,[64] the phyllites, greenstones, and chlorite schists of the Okanogan Valley in Washington are regionally metamorphosed, and on this earlier metamorphism is superposed the high-grade contact metamorphism of the intrusions.

In British Columbia to the north the metamorphism of the Shuswap rocks is considered Jurassic and early Cretaceous in age and was caused by the intrusions and associated orogeny, but it is likely that one or more episodes of dynamic metamorphism preceded the contact metamorphism. In correspondence Cairnes says:

> There is little doubt that such Carboniferous formations as the Cache Creek, Anarchist, Chilliwack, Hozameen, and Kobau were folded and subjected to some metamorphism prior to the main period of batholith intrusion. The intrusive bodies definitely cross-cut the folded structures and are themselves relatively fresh and unstrained. However, it is quite uncertain as to whether the Carboniferous strata were subjected to one or more deformations. It seems reasonably certain that, if more than one, the last occurred in Cretaceous or in very late Jurassic time, as it has affected intrusive bodies, such as the Custer granite-gneiss and the Osoyoos and Fairview batholiths of late Jurassic age, presumably. The Osoyoos and Fairview batholiths are involved in the folding and metamorphism of the Kobau group and are definitely older than the bulk of the batholiths of the area.
>
> In southwest British Columbia it seems generally true that formations of Triassic and earlier age are more severely deformed and more completely altered that those of Jurassic or later Mesozoic times, and perhaps the consensus of opinion would be that this early deformation was the result of an orogeny forerunning the emplacement of the enormous quantities of batholithic materials in the late Jurassic and succeeding Cretaceous and Tertiary periods. Where fossiliferous evidence is lacking, a principal difficulty in this part of the province has been to separate, either lithologically or structurally, the Triassic from late Paleozoic formations, rather than the Triassic from those of later age. Farther north, in central British Columbia, the situation seems different. There Permian and Carboniferous

[64] See ftn. 46.

formations are more deformed than the Triassic (probably all Upper), Jurassic, and early Cretaceous rocks. The difference is probably related quite closely to a variable history of batholithic intrusion. In the south, the principal periods of intrusion seem to have been in later Jurassic, post–Lower Cretaceous, and mid-Tertiary times; in the north there are reasons for believing that the earliest principal period of intrusion was in Triassic (probably early or pre-Upper) time, and others of consequence in pre–Upper Cretaceous and pre-Eocene (Laramide) times. Much of the information however, is speculative to say the least, and there is an aggravating lack of sedimentation where stratigraphy could be of most help, a dearth of key fossils where they would be most useful, and an inconsistency in the interpretation of plant and invertebrate remains from the same beds that is little short of exasperating.

B. B. Brock[65] and James Gilluly[66] both believe the metamorphism of the Shuswap rocks to be of dynamic origin. Some petrologists believe that the presence of magmatic solutions is necessary to produce a schist, and, if so, the dynamic metamorphism of Gilluly may be related to the Jurassic intrusions. The problem of pre-Jurassic orogeny, therefore, is not clear as a result of the study. Cairnes[67] concludes that the foliation of the Shuswap is primarily an inherited structure, conformable with the original bedding, and that prevailing structural trends, as indicated by the foliation, may some day serve a useful purpose in demarcating separate formations whose age and structural history may differ. He points out that the structures on the whole are gentle and that this is a diagnostic feature of the terrane and bears directly on the geologic history, namely, that they were not much folded before or during the granitic intrusions.

[65] "The Metamorphism of the Shuswap Terrane of British Columbia," *Jour. Geol.*, Vol. XLII (1934), pp. 673–99.

[66] "Mineral Orientation in Some Rocks of the Shuswap Terrane as a Clue to Their Metamorphism," *Amer. Jour. Sci.*, Vol. XXVIII (5th ser., 1934), pp. 182–201.

[67] See ftn. 51.

ALEXANDER DIVISION

Extent.—The Alexander division of the Pacific trough is named for the Alexander Archipelago of southeastern Alaska, but the division includes, besides the islands, parts of the crust along the mainland, now largely occupied by the great Coast Range batholith. Paleozoic rocks are exposed from the St. Elias Range southward to Dixon Entrance; but from there to the south end of Vancouver Island only Mesozoic rocks crop out. The batholith separates the sediments of the Alexander system from Paleozoic and Mesozoic rocks to the east, which are as yet little studied but probably are, in part, of the Pacific trough facies and, in part, of the Rocky Mountain trough facies.

Pre–Middle Devonian phase.—The relations of the pre–Middle Devonian formations to one another are everywhere doubtful.[68] The Wales group, part of which seems to be of pre-Ordovician age, is overlain in places by beds of Lower and Upper Silurian age, but whether conformably or unconformably is not known. The Wales rocks are relatively much more deformed and metamorphosed than the known Silurian formations, but it is possible that this difference may be due to excessive metamorphism resulting from the intrusion of large masses of igneous rock that are only slightly exposed at the surface. Wales rocks have not been observed in contact with rocks of known Ordovician age, and the relations between them are not known. The Wales rocks were originally sandstone, shale, lava, and tuff.

[68] See ftn. 54.

Graywacke and slate formations of the Ordovician and Lower Silurian are isoclinally folded with nearly vertical dips wherever found, regardless of the effects of the igneous intrusions. The Upper Silurian beds, on the other hand, are metamorphosed and folded locally in connection with the igneous masses but, in general, not so strongly as the underlying graywacke and slate. There are two possible explanations for this: the Ordovician and Lower Silurian beds may have been folded before the deposition of the Upper Silurian, or the more intense folding of the older beds has resulted from folding of the incompetent graywacke and slate beneath arches of the thick, massive Silurian limestone, which acted as a competent bed. There is no doubt that the difference in competency has been an important factor in producing the difference in folding between the two groups of rocks, but whether it is the only factor is questionable.[69]

The volcanics, the graywackes, the conglomerates, the suggested unconformities, and perhaps the difference in degree of folding and metamorphism of some of the formations all point to the existence and close vicinity of an orogenic belt, where movements were occurring. The belt of major orogeny lay to the west, and the site of preponderant deposition was in the trough, to which, recurrently perhaps, the crustal movements spread and disturbed the sediments and lava flows.

Middle Devonian phase.—Middle Devonian formations overlie the Lower and Upper Silurian beds unconformably. The relation is clearly exposed on several islands in the archipelago.[70] The Middle Devonian strata in the Klamaths, it will be recalled, overlie the older formations unconformably. The identification of a crustal disturbance at the same time at both places, even though its details remain unknown, emphasizes the magnitude of the orogeny represented by the unconformity.

Some suggestion of an unconformity between the Middle and the Upper Devonian is noted at two places (Coronados Islands—a small group at the mouth of Port St. Nicholas–Prince of Wales Island—and small islands in Trocadero Bay).

Permian phase.—In the Ketchikan district the limestone division of the Permian overlies the Upper Devonian unconformably. In the Keku Islands of the Petersburg district the lower division of the Permian seems to be unconformable on formations as old as Silurian. At the east end of Suemez Island the Permian appears to rest unconformably on the Upper Devonian.[71]

Lower Triassic phase.—The basal conglomerates of the Upper Triassic formations in the Alexander Archipelago at many localities carry abundant fossiliferous limestone cobbles of Devonian and Permian age. At most places the Upper Triassic beds overlie the upper division of the Permian; but locally they overlie Devonian formations.[72]

A basal Triassic conglomerate has been observed in a number of districts in British Columbia and the Yukon, in addition to southeastern Alaska. S. J. Schofield[73] has listed the places as follows: Cameron Lake on Vancouver Island, Mussel Inlet, Garibaldi region, Britannia map area, Coquehalla, Bridge River, Stikine River, Laberge area, Slo-

[69] *Ibid.*

[70] *Ibid.*

[71] *Ibid.*

[72] *Ibid.*

[73] "Cascadia," *Amer. Jour. Sci.*, Vol. CCXXXIX (1941), pp. 701–14.

can, Kootenay, and Kamloops (see map, Fig. 6).

The conglomerate consists of metavolcanics, mica schist, metaquartzite, diorite or gabbro, and, very persistently, granite, granodiorite, and quartz-diorite pebbles and boulders. In several places it is massive, with boulders up to 8 inches in diameter. In the Laberge area the massive conglomerate is 700 feet thick and consists of well-rounded boulders, 2 inches–2 feet in diameter, and predominantly of volcanic porphyry and graywacke. Granodiorite boulders are abundant, and limestone boulders are scattered. The silicic plutonic boulders could not have been derived from the Jurassic batholith because the Triassic conglomerates are cut and nearly everywhere metamorphosed by them.

Arkose occurs with the conglomerate in the Britannia map area. The lack of rounding of the grains, the freshness of the plagioclase, and the thickness of the unstratified beds have been taken to signify rapid accumulation and a near-by source. The conglomerates probably indicate the same conditions. Of special interest is the observation that the near-by source was a land in which silicic plutonic rocks were exposed.

The Wrights[74] postulated a northeasterly trend to the folds, which they believed was the dominant structure at the close of the Paleozoic over all southeastern Alaska. The present structural trends are northwesterly, and, according to Buddington,[75] the Wright concept would need, in the face of its exceptional nature, special proof. Buddington saw evidence of northeasterly folds at only one place, and he does not believe that the contention is proved. Nevertheless, he believes that the unconformable relations of the Upper Triassic sediments and the older ones indicate a time of marked disturbance, perhaps of major orogeny. Schofield points out that the Triassic beds in places have the same strike and dip as the underlying ones and that, although in those places the early Triassic orogeny seems to lose importance, the theory of divergence in trend of folds of an earlier orogeny with those of post-Triassic orogeny is not supported. The basal Triassic conglomerates reflect orogeny in a near-by area, and the absence in places of an angular unconformity where the conglomerates were deposited does not minimize the importance of the orogeny.

[74] F. E. and C. W. Wright, "Lode Mining in Southeastern Alaska," *U.S. Geol. Surv. Bull. 284* (1906), pp. 30–54.

[75] See ftn. 54.

VOLCANIC ARCHIPELAGO

CONCEPT OF A WESTERN LANDMASS

In the opinion of several geologists, the source of the sediments, and especially of the volcanics, of the Cordilleran geosyncline in Paleozoic time was to the west. Schuchert named the landmass from which they came "Cascadis" (*Historical Geology* [1924]) and characterized it as the greatest of all "borderlands." In the Mesozoic era he believed Cascadis was divided into two smaller landmasses, each with shorelines farther west than the Paleozoic one. The Schuchert concept of Cascadis seems to be the most widely accepted theory today among paleontologists and stratigraphers. Deiss[76] recently depicted the shoreline of Cascadis during the Cambrian in about the position that Schuchert illustrates it, namely, at the western margin of the southern Rocky Mountain trough, the Montana dome, and the northern Rocky Mountain trough (see map, Fig. 1).

[76] See ftn. 4.

Schofield[77] has reviewed the concept of "Cascadia" and agrees that a western landmass existed; but, on the basis of Proterozoic, Silurian, and Triassic conglomerates of British Columbia and southeastern Alaska, he regards it as having lain west of the present west coast of North America, except during the Proterozoic (Beltian), when, he thinks, the shoreline was just west of Kootenay. Cairnes[78] has shown that the Shuswap terrane is not all pre-Cambrian rock and therefore not a former land area, but that, on the contrary, it is the metamorphosed facies of rocks of several periods and that it was the site of deposition during at least part of the Paleozoic. The Shuswap terrane has been depicted as part of Cascadis by Schuchert and others, but this seems now disproved.

The previous pages on the great Cordilleran geosyncline—its divisions, sediments, and deformation—have suggested several stimulating lines of evidence by which the position and constitution of the lands from which the sediments came can be deciphered. The nature of the sediments alone is very informative; and this, together with their distribution, provides enough data to reconstruct a general picture of the western lands.

EVIDENCE OF A WEST-LYING ARCHIPELAGO

Volcanic rocks.—The abundance of volcanic rocks, mostly tuffs and lavas, in the Pacific trough, with none in the eastern, has been noted. The volcanoes were not situated along a landmass between the two troughs because such an elevation probably did not exist except in the south in Carboniferous time, when the Manhattan geanticline rose. If a medial land area had existed and had been the site of volcanoes, the eastern trough would have received as much volcanic material as the western. It is therefore concluded that the volcanoes were aligned along the western flank of the Pacific trough. They are known to have been especially numerous opposite the Klamath and Alexander troughs and were active at intervals in each period from pre-Ordovician to the Present.

In the modern geologic picture, rows of active volcanoes are on the concave side of island arcs or archipelagos, but on the larger islands, such as Japan, the volcanic rocks are widely distributed on both sides. It therefore seems of some significance that the Klamath and Alexander troughs are on the concave sides of what would be the west-lying island arcs.

The great bulk of the lavas in both the Klamath and the Alexander troughs are andesites. Some basalts occur in the Klamaths, but only andesitic lavas have been found in the Alexander trough. This is especially instructive because the volcanoes of the island arcs, both modern and ancient, have emitted chiefly andesites. W. H. Hobbs[79] has recently reviewed this distribution and has drawn an andesite-basalt line which separates the basalts of the volcanoes of the ocean floor from the andesites of the island arcs in the western and southern Pacific. Rarely do appreciable quantities of andesite occur on the mainland opposite an archipelago. Inspection of the geologic map of eastern Asia (Fig. 7) reveals abundant andesite on the Japanese archipelago but an absence of it on the Asiatic mainland across the Sea of Japan and the Sea of Okhotsk.

It may be concluded, therefore, that the andesitic nature of the preponderance of volcanic material in the western trough of the Cordilleran geosyncline

[77] See ftn. 73.

[78] See ftn. 51.

[79] "Mountain Growth: A Study of the Southwestern Pacific Region," *Proc. Amer. Phil. Soc.*, Vol. LXXXVIII (1944), pp. 221–68.

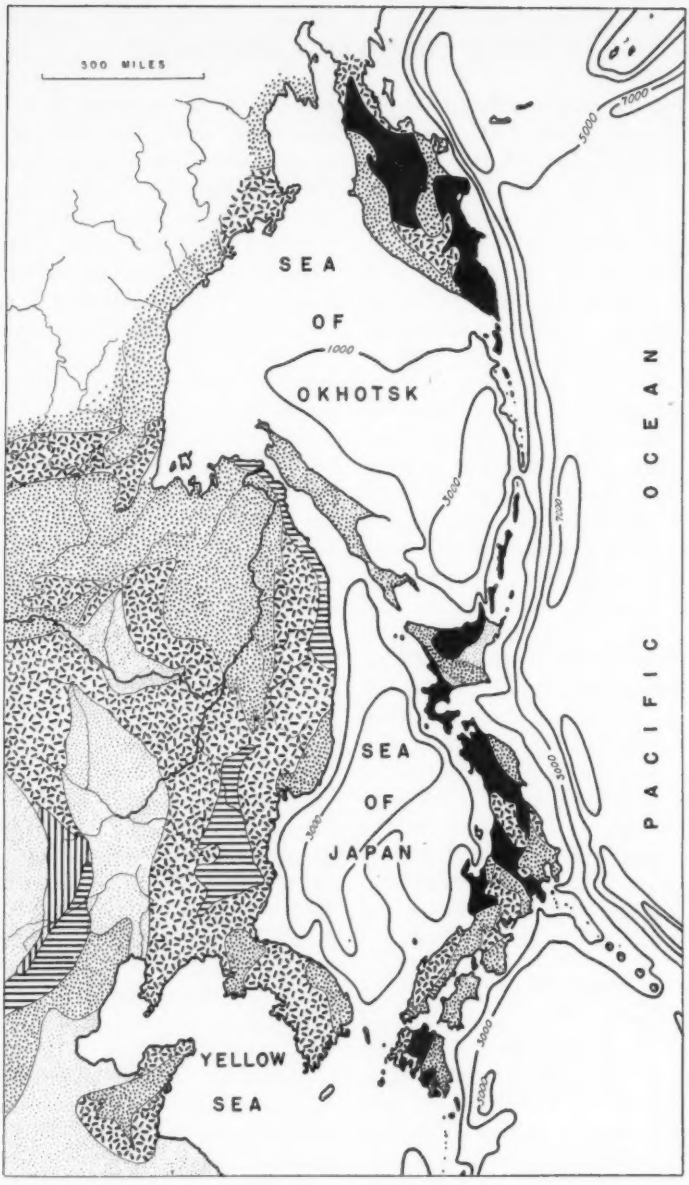


FIG. 7.—Generalized geologic map of the Japanese Archipelago and the eastern part of Asia. Isobaths are in meters. Coarsely stippled areas are those chiefly of sedimentary rocks, but with large areas of Archean gneisses and schists and some smaller areas of intrusive and extrusive rock. Finely stippled areas denote alluvium. Hachured areas as those of plutonic rocks, chiefly granite to granodiorite, but with considerable areas of Archean gneiss and schist and some sedimentary rocks. Solid black areas are andesite. Horizontally ruled is basalt and vertically ruled is trachyte.

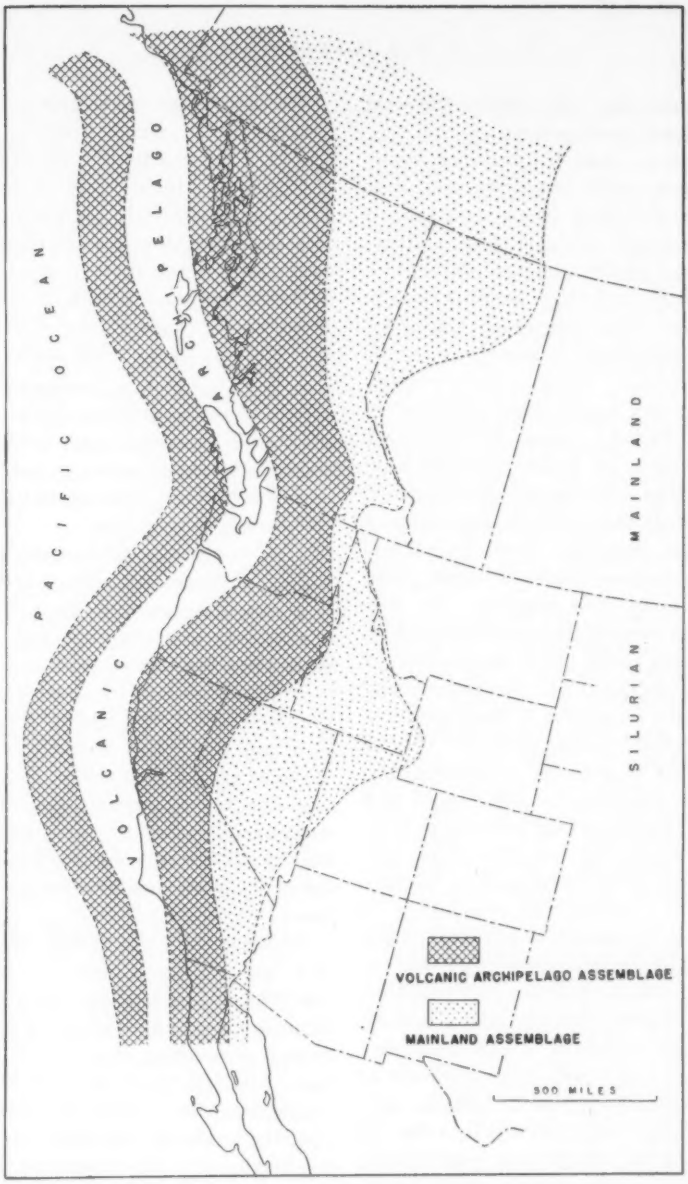


FIG. 8.—The volcanic archipelago and its relation to the sediments of the Paleozoic Cordilleran geosyncline. The map is generalized for the Silurian period on the assumption that the Copley volcanics of the Klamath Mountains are Silurian in age and correlate with the Silurian volcanics and graywackes of the Alexander Archipelago. The volcanic archipelago assemblage consists of andesitic volcanics in many forms, graywacke, conglomerate of andesite and granitoid rocks, massive limestones and coarse intra-formational limestone conglomerates, chert, arkose, dark shale, and siliceous shale (all the above varieties are generally found now in their metamorphosed form). The mainland assemblage consists of orthoquartzite, arkosic sandstone, sandstone, conglomerate (generally pea and pebble size, composed of quartzite and quartz pebbles), limestone and dolomite, cherty limestone and chert, and various shales and siltstones.

also indicates that the land to the west was a volcanic archipelago.

Graywackes, arkoses, and conglomerates.—A graywacke is a dirty sandstone in the sense that a clean sandstone is composed largely of quartz grains. Graywackes have an abundance of slate, phyllite, argillite, and chert fragments. The grains come from previously deposited clastics that have suffered low-grade metamorphism.[80] From a study of graywackes in the Appalachian geosyncline, from the Alpine molasse, and from the Siwalik strata of India, Krynine concludes that graywackes are due to erosion of previously deposited sediments in a geosyncline that had been folded and somewhat metamorphosed by widespread orogeny along the margins. He also thinks it is possible that geanticlines with geosynclines could bring the previously deposited sediments to the surface and result in the formation of graywackes.

Buddington[81] states that the Silurian graywackes, in general, of southeastern Alaska are composed of particles of rock similar to the kinds that form the pebbles and cobbles in the conglomerates with which they are interbedded and, in addition, of a considerable percentage of plagioclase, potassic feldspar, and quartz grains. The conglomerates are largely made of andesite pebbles and boulders; but slate, diorite, rhyolite, and limestone pebbles are abundant, if not dominant, in some conglomerates. One specimen of graywacke of Devonian or Silurian age, for example, consisted of particles of andesite, felsite, plagioclase, granophyre, quartz, spherulitic rhyolite, and orthoclase, with a chloritic and slightly calcareous groundmass.

[80] P. D. Krynine, "Paleogeographic and Tectonic Significance of Graywackes" (abstr.), *Bull. Geol. Soc. Amer.*, Vol. LII (1941), p. 1916.

[81] See ftn. 54.

The association of the graywackes and conglomerates that Buddington describes is very revealing of their origin and substantiates Krynine's conclusions. The conglomerates in themselves are indicative of a volcanic archipelago to the west and deserve further mention. The following is a résumé of the Silurian conglomerates according to Buddington. Varieties of conglomerate are as follows:

1. A conglomerate composed almost wholly of well-rounded andesite or andesite porphyry cobbles and boulders; the matrix may be calcareous, and lenses of limestone are intercalated, but limestone cobbles are sparse.

2. A conglomerate composed almost wholly of limestone cobbles or boulders in a limestone or andesitic tufflike matrix; this type is rare, but beds 100 feet thick have been noted.

3. Peculiar conglomerates intermediate between 1 and 2, consisting of pebbles and cobbles of andesite and limestone in a greenish tufflike matrix.

4. A homogeneous-appearing rock composed of fragments of andesite in a matrix of the same material; the structure is that of a conglomerate or waterworn breccia.

The limestone fragments are usually of a dense-textured limestone typical of the Silurian, and many carry fossils of Silurian age. The fossils are the same as from the overlying limestone. It is, therefore, believed that the limestone conglomerates are intra-formational and that the limestone fragments are of practically the same age as the volcanic fragments. Vertical movements of the sea bottom, perhaps local, must have accompanied the volcanism and must have resulted in contemporaneous erosion and submarine slumping of slightly compacted fine lime mud. A part of the volcanic material, at least, must have been

erupted from central volcanoes, which were built up above the surface of the ocean and were thus subjected to erosion.

Although recognizing unsolved elements in the problem of origin of the graywackes, conglomerates, and limy argillaceous beds, Buddington visualizes a sedimentary environment as follows; the great lens-shaped beds of conglomerate may be local deposits made by torrential streams, and the graywacke may be in part the more finely comminuted peripheral marine equivalent. The calcareous shale and argillaceous limy beds, which are locally intercalated with the clean, thick-bedded limestone, may be in part the more distant offshore equivalent of the conglomerate and graywacke.

The limestone is in part dense white on fresh surfaces and massive, with only rare, if any, evidence of stratification. Beds as thick as 2,000 feet have been observed. In part it is interbedded with thin-layered limestone, nodular and shaly limestone, calcareous shaly argillite, dense platy siliceous layers, green-gray shale, and sparse buff-weathering sandstone. The massive limestone seems to be due to rapid deposition, and, where clean, the site of accumulation was sufficiently distant from land so as not to have received any clastic material. Volcanic activity has been thought of as contributing to the deposition of the limestone through the activity of magmatic waters or meteoric waters draining from a volcanic terrane, but the chemistry and oceanography of the problem have not been worked out.

Schofield[82] has already been cited as having discussed the problem of granitoid pebbles and cobbles in the conglomerates of several periods, especially the Triassic. Buddington refers to them also. In one locality the Britannia map area of British Columbia, an arkose is described as composed of irregular grains of quartz, plagioclase, orthoclase, and sericite schist. The lack of rounding of the grains, the freshness of the plagioclase, and the considerable thickness of the unstratified beds prove that the material accumulated rapidly and was transported only a short distance from a source of granitoid plutonic rocks. Buddington failed to trace the granitoid clastics to their source, despite the fact that their size and abundance indicated to him a nearby local origin. It seems necessary, he believes, to assume that granitoid intrusions existed in a land that formerly stood to the west, where only the Pacific Ocean now lies.

Krynine[83] has studied the tectonic significance of arkoses and concludes that they are deposited just after a granitoid terrane has been uplifted and while it is being vigorously dissected. They are derived from the deformed geosyncline into which granitoid rocks have been intruded. The plutons become exposed by erosion of the mountains created by orogeny and then are uplifted in a further stage of deformation and vigorously eroded.

Granite plutons are seldom exposed in arcs of small volcanic islands. We must look to the larger islands of an archipelago for the source of granitoid conglomerates and arkoses. The geologic map of the Japanese Archipelago (Fig. 7) shows extensive areas of granitic intrusions and pre-Cambrian gneisses, which could furnish the necessary material. A major archipelago like the Japanese has had a long orogenic history and is composed of rocks that will make not only graywackes but also arkoses. Such a one seems to have been the source land of

[82] See ftn. 73.

[83] See ftn. 80.

the sediments of the western part of the Cordilleran geosyncline.

Orthoquartzite and chert.—The eastern trough lacks the volcanics, graywackes, and arkoses, but it has a dominant lithology that is exceedingly scarce in the western trough—sandstones cemented by silica. These are commonly called "quartzites," such as the Tintic, Brigham, Bingham, Weber, Wells, Quadrant, Flathead, Deadwood, etc.; but perhaps the names "orthoquartzite" and "quartzose sandstone" would safeguard against the misconception that they are metamorphic rocks. Some of the Proterozoic quartzites in the Rocky Mountain trough are regionally metamorphosed, but it is very doubtful if any of the Paleozoic and Mesozoic quartzites are affected in the least.

According to Krynine,[84] sedimentary orthoquartzites and quartzose sandstones originate either as deposits following prolonged chemical weathering of a terrane or though re-working of pre-existing quartzose sediments. The first group generally develops after chemical decay in peneplained regions. The shallow seas into which the sands were deposited were, at the time, precipitating silica, and, as a result, orthoquartzites were formed. If part of the sea bottom is removed from sand deposition, considerable beds of chert will form. If Krynine's postulate is true, it would appear that the sand grains of the orthoquartzites were derived from the mainland of the continent. It does not seem possible that they could have come from the west, where volcanic activity dominated. Associated with the Paleozoic quartzites are several limestone formations, 500–2,000 feet thick, and several somewhat thinner shale formations. The assemblage of quartzite, shale, and limestone supports the conclusion of a mainland origin.

Great beds of chert are present in the sediments of the volcanic archipelago. Extensive beds of chert and cherty limestone are present in the Rocky Mountain trough, as well as in the inland basins and shelfs of the mainland, and therefore the factors governing the precipitation of the silica are probably several. Its transportation in solution in marine currents may result in precipitation at a great distance from its source. I find it easy to believe that a large part of the silica originated in the volcanic activity of the archipelago; that some of it was carried by currents across the seas between the archipelago and the mainland free from the area of deposition of volcanic material; and that it was precipitated copiously in the shallow seas of the eastern trough and mainland shelf, where, from place to place and from time to time, clay, lime mud, or sand was accumulating. The problem needs special attention beyond the limits possible here, but the distribution of the cherts and orthoquartzites fits in nicely, if only theoretically, with the postulate of a western volcanic archipelago.

Distribution of troughs and sediments.—The pre-Devonian troughs of the Cordilleran geosyncline are isopached in Figure 1. The spread of data and the amount of interpretation have been discussed on previous pages. In brief review it is clear that the contouring of the western trough between the Alexander Archipelago and the Klamath Mountains is principally a guess, but, at least, a logical one and not at variance with known information. The Klamath trough is contoured on the assumption of a Paleozoic age of the Copley, Chanchelulla, and Salmon formations. The western flank of the northern Rocky Mountain trough is

[84] *Ibid.*

masked by metamorphism, so that its exact configuration is not known. Also the continuation of the trough northward from Jasper is fairly speculative. Elsewhere in the great geosyncline, substantial data support the contouring.

The pattern of the troughs, together with a postulated western volcanic archipelago, reminds one of the seas and archipelagos of the western Pacific, and it is natural to compare the two. In doing so it must be borne in mind that in our own western geosyncline we have the sedimentary record through the geologic periods, whereas in the western Pacific Ocean we have the shorelines of the moment, the distribution of the rocks on the archipelagos and the mainland adjacent to the seas, but practically no information about the sediments that are forming in the seas. A few dredgings have been made in a few places and have been reported on, but these represent at best only the topmost layer. Under the great seas between the archipelagos and the mainland we have little idea where troughs of greatest accumulation are or what the nature is of the sediments in the troughs below the surface. Instead of making a comparison, we find ourselves supplying the lost parts of one with the known parts of the other and making a complete geologic province, for we have the sedimentary record in one and the source of the sediments and the site of their deposition in the other. Knowing what we do of the origin of sediments, it is not difficult to recognize the fit or misfit of the parts.

In the first place, the shape and scale of the geosynclinal elements of the two regions is comparable (cf. Figs. 7 and 8). The Japanese Archipelago including Kamchatka was selected for comparison because it is the closest modern parallel that could be found. The curvature of the arcs, their convexity toward the Pacific, their width and length, are conspicuously alike.

In the second place, the geology of the Japanese Archipelago is somewhat the same as that postulated for the source land of the sediments of the Pacific trough of the Paleozoic Cordilleran geosyncline. If the Tertiary and Cretaceous strata are imagined removed from the Japanese islands, then the proper rocks and terrane are present to supply such sediments as are found in the Pacific trough. The most abundant rocks mapped in the Japanese Archipelago are as follows: andesite, granite, syenite, schistose granite, gneiss, schist, slate, chert, sandstone, limestone, diorite, pyroxenite, amphibolite, gabbro, and trachyte, in approximately decending order of abundance. From the nature and distribution of these rocks it is realized not only that the Japanese Archipelago and related seas are a comparable example but that their history probably ran through the Paleozoic era in a way appreciably like that of the Cordilleran geosyncline. The highly generalized geologic map of the Japanese Archipelago and the adjacent mainland (Fig. 7) is presented to show the sources of the sediments and the depths of the seas into which the sediments drain.

Figure 8 depicts the two great assemblages of sediments in the Cordilleran geosyncline as they were deposited during Silurian time. The Silurian was selected for illustration because it seemed to give a pattern that more closely simulates that of the Japanese region. In other periods, either volcanism was not prominent opposite both the Klamath and the Alexander troughs at the same time, or the seas did not spread over the eastern trough. Deep-water sediments, such as must be accumulating in the Sea of Japan and the

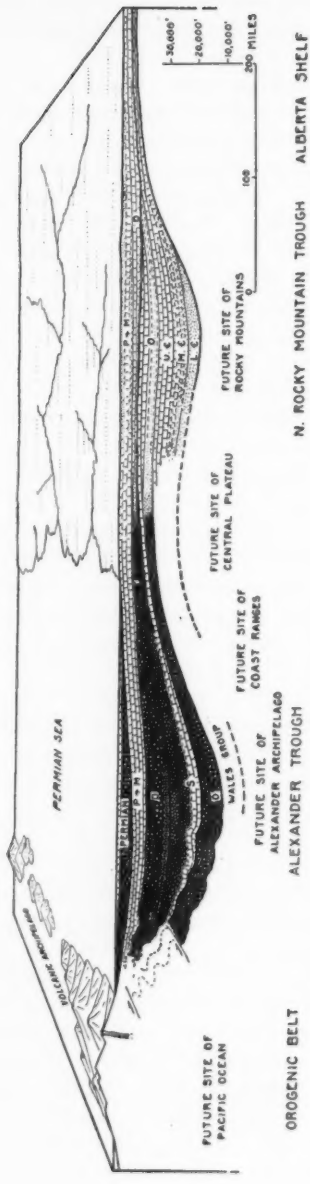


FIG. 9.—Cordilleran geosyncline in southeastern Alaska and British Columbia at the close of the Permian. The dark formations of the Alexander trough with white triangles are volcanics, and those with white triangles and round dots are graywacke. The other symbols are conventional.

Sea of Okhotsk, may be present in the Cordilleran geosyncline, but they have not been recognized.

A consideraton of the sedimentary conditions about volcanic archipelagos and the comparison of these with the mainland assemblage stimulate thoughts that ramify into many aspects of sedimentation but which are outside the objectives of this article. It must suffice to conclude that the distribution of sediments in the Cordilleran geosyncline indicates that a volcanic archipelago existed west of the western trough during the Paleozoic era.

ARCHIPELAGO AND OROGENIC BELT

The sedimentary evidence that establishes a great volcanic archipelago on the west side of the Cordilleran geosyncline at the same time indicates the existence there of an orogenic belt, because, from all we know, similar archipelagos in other parts of the world are the result of crustal movements in zones of active deformation.

Added to the sedimentary evidence of a Paleozoic orogenic belt is the dynamic evidence in the form of numerous unconformities between stratigraphic systems in the Pacific trough. Further dynamic evidence is the metamorphism of the trough's formations and, in addition to this, the convincing observation that the grains of the graywackes and the pebbles of the conglomerates were derived from already dynamically metamorphosed rocks of Paleozoic age. These, in short, are the lines of evidence that support the theory of a great orogenic belt to the west of the Cordilleran geosyncline during Paleozoic time. The theory is illustrated ideally in Figure 9.

CORRELATION OF THE EROSION SURFACES OF THE SOUTHERN APPALACHIANS

PAUL R. SHAFFER
Ohio Wesleyan University

ABSTRACT

Zonal profiles and field observations indicate that one peneplain, two erosion surfaces, and a minor surface or strath are present in the southern Appalachians, not considering present or recent valley floors. These surfaces are correlated with the well-recognized erosion surfaces of the northern Appalachians. The effect of structure upon the development of the erosion surfaces of the southern Appalachians is considered.

INTRODUCTION

The existence of erosion surfaces in the southern Appalachian region has been demonstrated by many workers.[1] Although these surfaces have been described in detail and named, little attention has been given to their correlation with the well-established surfaces of the northern Appalachian region. The purpose of this study is to establish a correlation between the erosion surfaces of the southern and northern Appalachian areas.

The index map (Fig. 1) shows the area of detailed study. The area chosen has the advantage of containing in the eastern part the folded structures of the Valley and Ridge and in the western part the broad Cumberland Plateau, where the structure is relatively simple and interpretation is easier than in the folded region. The nine quadrangles to the south are mapped in folios of the *Geologic Atlas of the United States*.

As early as 1890, Davis[2] suggested that the erosion surfaces of the northern Appalachians continue southwestward over the entire Appalachian region. In 1894, Hayes and Campbell[3] published an excellent and comprehensive paper on the geomorphic development of the southern Appalachians, in which they recognized two peneplains. Other students have already been mentioned, and the erosion surfaces recognized by these workers and the names applied to them are summarized in Table 1. The names are arranged in descending order from highest (oldest) to lowest (youngest) and are arranged to suggest correlations, where this is possible.

Recently, W. S. Cole[4] showed convincingly that in the northern Appa-

[1] W. M. Davis, "The Geologic Dates of Origin of Certain Topographic Forms on the Atlantic Slope of the United States," *Bull. Geol. Soc. Amer.*, Vol. II (1890), pp. 545–81; C. W. Hayes, "The Rome, Georgia-Alabama Folio," *Geol. Atlas of the United States* (1900), No. 78; C. W. Hayes and M. R. Campbell, "Geomorphology of the Southern Appalachians," *Nat. Geog. Mag.*, Vol. VI (1894), pp. 63–126; A. Keith, "Some Stages of Appalachian Erosion," *Bull. Geol. Soc. Amer.*, Vol. VII (1895), pp. 519–25; G. W. Stose and H. D. Miser, "Manganese Deposits of Western Virginia," *Va. Geol. Surv. Bull. 23* (1922), pp. 1–200; F. J. Wright, "The Physiography of the Upper James River Basin in Virginia," *Va. Geol. Surv. Bull. 11* (1925); "Erosional History of the Blue Ridge," *Jour. Sci. Lab. Denn. Univ.*, Vol. XXIII (1928), pp. 321–44; "The Older Appalachians of the South," *ibid*, Vol. XXVI (1931), pp. 143–250; "The Newer Appalachians of the South," *ibid.*, Vol. XXIX (1934), pp. 1–107; K. Ver Steeg, "Erosion Surfaces of the Appalachians," *Pan.-Amer. Geol.*, Vol. LVI (1931), pp. 267–84; "Correlation of Appalachian Peneplanes," *ibid.*, Vol. LXXIII (1940), pp. 203–10.

[2] Ftn. 1.

[3] Ftn. 1.

[4] "Nomenclature and Correlation of Appalachian Erosion Surfaces," *Jour. Geol.*, Vol. XLIX (1941) pp. 129–48.

lachians there is one peneplain, two erosion surfaces, and one strath stage. These surfaces are recognizable over the entire northern Appalachian district. Although local names are used for convenience in designating various surfaces, it was shown that satisfactory correlations can be made in the northern portion of the Appalachians.

Detailed study of the selected area in the southern Appalachians indicates that the same number of surfaces is present in both the northern and the southern Appalachians. Through the use of projected profiles, connecting the area of detailed study in the south with the area of demonstrated surfaces in the north, a correlation was established. This correlation is shown in Table 2.

METHODS OF STUDY

Two types of projected profiles were used in this study. For the district extending from the southern boundary of the Sewanee, Chattanooga, and Cleveland quadrangles to the middle of the Wartburg, Briceville, and Maynardville quadrangles, east-west lines were drawn across the maps at 1-inch intervals, and a zonal profile was made for each approximately 2-mile distance between the lines. The zonal profile was drawn on Bristol board, cut out, and mounted in a frame (Pl. I). For the Beattyville–Maynardville quadrangles a simple projected profile was made, the base line of which was along the western boundary of the quadrangles (Fig. 2).

The zonal-profile type has the advan-

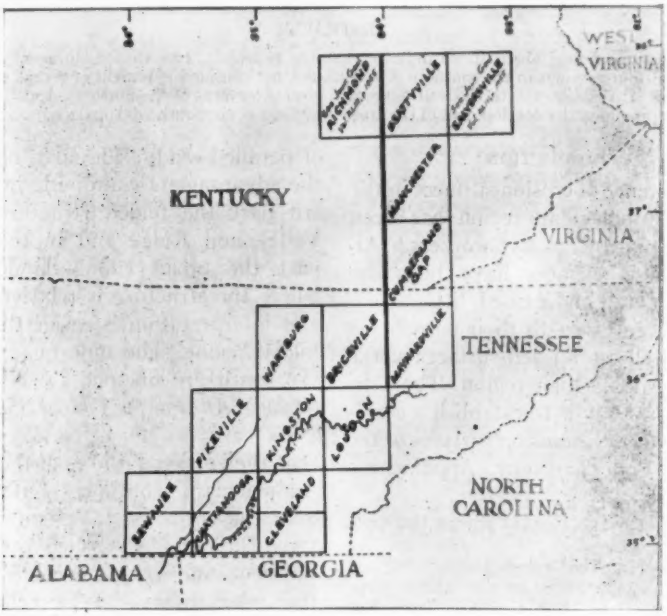
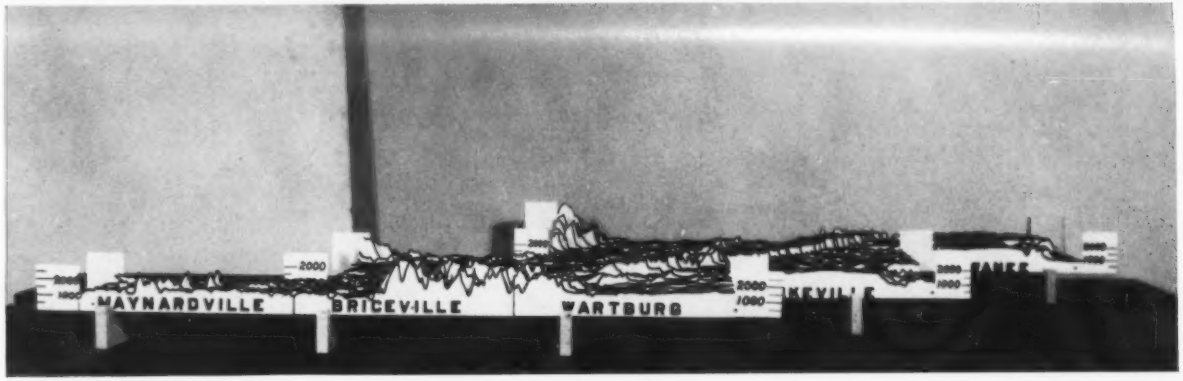
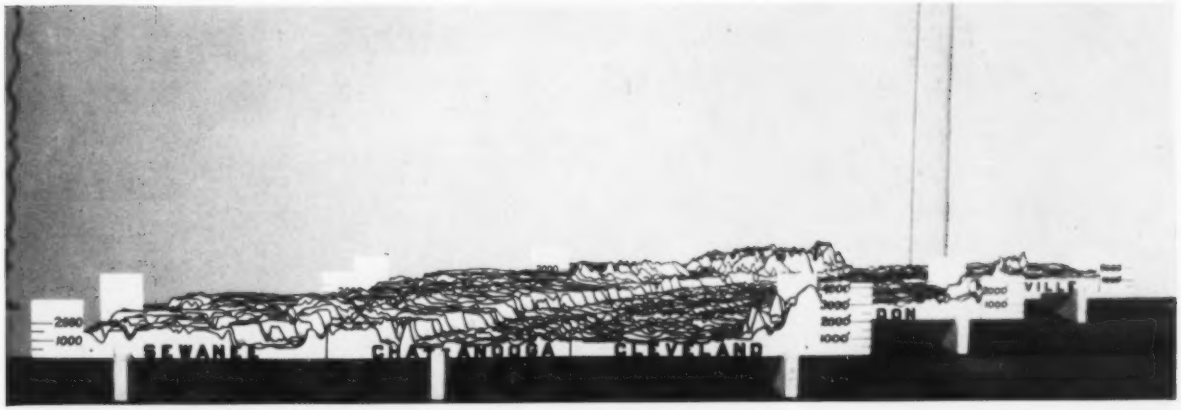


FIG. 1.—Index map, showing the area of detailed study in Tennessee and the quadrangles studied in Virginia and Kentucky. The heavy line on the west border of the Beattyville-Maynardville quadrangles was the base line for the projected profiles of this region. The east-west line through the center of the Sewanee-Cleveland quadrangles indicates the position of the structural section.

PLATE I



A, The model from north to south



B, The model from south to north

TABLE 1

Hayes and Campbell (1894)	Keith (1895)	Hayes (1900)	Stose and Miser (1922)	Wright (1928)	Ver Steeg (1931)	Wright (1931)	Wright (1934)	Ver Steeg (1940)	Shaffer (This Article)
Cretaceous peneplain	3,700′–3,000′	Cretaceous peneplain, 1,600′ in northern portion of valley region on Rome quadrangle	Summit peneplain, 4,000′–3,500′	Blue Ridge Summit Peneplain = Upland Peneplain	Schooley (Kitattiny)	Upland = Schooley	Schooley = Upland	Schooley	Upland
	2,600′–2,000′		Upland peneplain, 3,000′–2,700′						Cumberland = Allegheny
	1,800′–1,500′		Intermediate peneplain, 2,200′–2,300′						
Tertiary peneplain	1,100′–1,000′	Tertiary peneplain	Valley floor peneplains	Appalachian Valley Peneplain = Asheville = Piedmont	Harrisburg	Harrisburg (Valley)	Harrisburg (Valley)	Harrisburg = Lexington (Worthington)	Valley = Lexington (Worthington)
	Partial cycle represented by terraces and bottoms at 600′–700′	Coosa peneplain, 630′ in Coosa Valley	Terraces and benches along major transverse streams	Young to mature valleys of present cycle	Coosa = Somerville = possibly Lexington (Worthington)	? ? ? Coosa = Somerville	Rock terraces veneered with stream gravels and boulders	Parker strath	Coosa = Somerville = Parker strath

tage of giving a regional picture in three dimensions when all the individual zonal profiles are drawn on Bristol board, cut out, and mounted in proper sequence in a frame. These cutouts have another advantage. They may be removed from the mounting frame, compressed until they resemble a profile of the type used in the Beattyville–Maynardville section, and photographed and studied from both directions and from above (Pl. II).

TABLE 2

Northern Appalachians		Southern Appalachians
Western Portion	Eastern Portion	
Upland	Upland	Upland
Allegheny	Schooley	Cumberland
Lexington (Worthington)	Harrisburg	Valley
Parker strath	Somerville	Coosa strath

To demonstrate the influence of structure and stratigraphy on the development of the erosion surfaces, an east-west structural section was made, from the folios, through the middle of the Sewanee, Chattanooga, and Cleveland quadrangles (Fig. 3). The impressions gained by study of the profiles and structure sections were checked during three summers in the field.

THE MODEL

A regional picture in three-dimensional form is shown by the cutout profiles, mounted in a frame in proper sequence to form the model. The erosion surfaces and their relationship to the significant physical features of the southern Appalachians are best seen when the model is viewed from the south (Pl. I, *B*).

The highest surface, the Upland peneplain, preserved in the Crab Orchard Mountains, may be seen in the central background. After the Upland peneplain was formed near sea level, uplift occurred, and the Cumberland erosion surface developed.

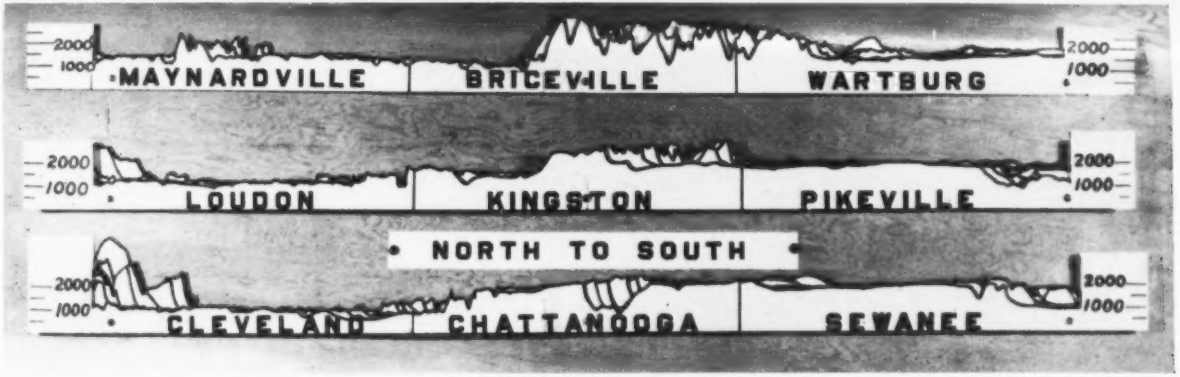
The Cumberland surface, the best-developed surface of the southern Appalachians, forms the top of the Cumberland Plateau and Walden Ridge Plateau and extends from the western border of the photograph eastward to the sharp topographic break approximately through the center of the photograph. This break, the Cumberland Escarpment, separates the Cumberland erosion surface above from the Valley erosion surface below.

Following uplift of the Cumberland surface, the Valley erosion surface, which increases in altitude northward, formed in the Valley and Ridge Province, shown in the eastern portion of the photograph. This surface has representatives in the hills in the Sequatchie Valley just east of the final *E* of "Sewanee" in the western foreground of the photograph.

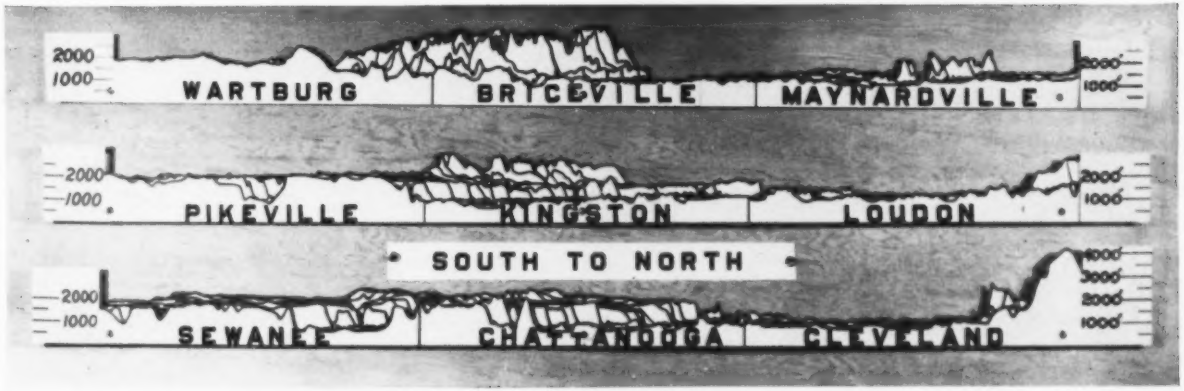
Again, after uplift of the southern Appalachians, the Coosa strath developed on weak rock along the major streams of the area. This surface is not well shown in the photograph because of mechanical difficulties inherent in projected profiles, but it may be seen in the field as gravel-covered stream terraces, about 650–700 feet above sea level. Slight uplift interrupted the extension of the Coosa surface, which had reached only the strath stage.

BEATTYVILLE–MAYNARDVILLE SECTION

The surface which extends completely across the Beattyville quadrangle at 1,300–1,400 feet and across the northern third of the Manchester quadrangle at 1,400–1,500 feet (Fig. 2) is the Lexington (Worthington) surface, which W. S.



A, Compressed profiles from north to south



B, Compressed profiles from south to north

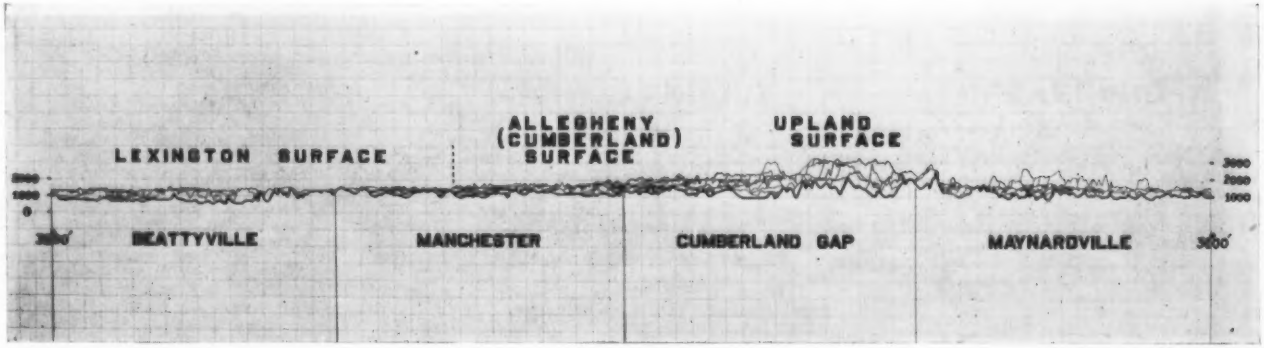


FIG. 2.—Projected profile of the Beattyville-Maynardville section. Base line along western boundary of the quadrangles. Vertical exaggeration approximately × 10.

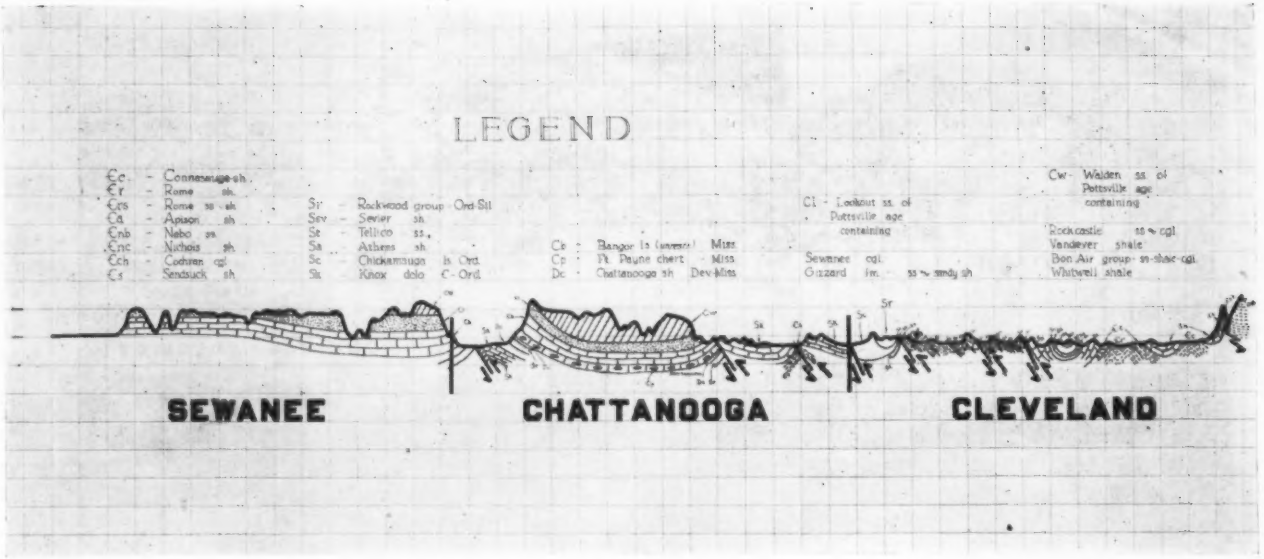

LEGEND
Cc - Conasauga sh
Cr - Rome sh
Crs - Rome ss - sh
Ca - Apison sh
Cnb - Nebo ss
Cnc - Nichols sh
Cch - Cochran cgl
Cs - Sendsuck sh
Sr - Rockwood group - Ord-Sil
Sev - Sevier sh
Se - Tellico ss
Sa - Athens sh
Sc - Chickamauga ls Ord
Sk - Knox dolo C-Ord
Cb - Bangor ls (lower) Miss
Cp - Ft Payne chert - Miss
Dc - Chattanooga sh Dev-Miss
Cl - Lookout ss of Pottsville age containing
Sewanee cgl
Gizzard fm ss ~ sandy sh
Cw - Walden ss of Pottsville age containing
Rockcastle ss ~ cgl
Vandever shale
Bon Air group - sh-shale-cgl
Whitwell shale
SEWANEE
CHATTANOOGA
CLEVELAND

FIG. 3.—Structural section of the Sewanee-Cleveland area. Section drawn east-west through the center of the quadrangles. Vertical exaggeration approximately × 10.

Cole[5] described on the Richmond, Beattyville, and Salyersville quadrangles in Kentucky. There appears to be general agreement about this surface among workers in the plateau region of Kentucky and Ohio.

At approximately a third of the distance across the Manchester quadrangle a distinct break is apparent. This break is interpreted as the juncture of the Lexington (Worthington) and the Cumberland (Allegheny) surfaces. The latter is the surface which extends across the Cumberland Plateau farther south and was called "Cumberland" by Hayes.[6] On the quadrangles to the south the parenthetical "Allegheny" will be omitted. The break just noted has been identified throughout the tract from central New York southward to the area of this study. It has been described by W. S. Cole[7] on the projected profiles of the New Martinsville quadrangle (1934), the Salyersville, Wayne, and Arnoldsburg quadrangles (1935), the Centerpoint, Freeport, and Shenango quadrangles (1937), and the Cambridge Springs and Honeoye quadrangles (1938). The geologic map of Kentucky shows no stratigraphic reason for the break, and it is therefore interpreted as an erosional feature.

At its juncture with the Lexington (Worthington) surface the Cumberland surface is at an elevation of 1,600 feet and rises southward on the Manchester quadrangle until it reaches 1,900 feet at the southern border. A long strath of the Lexington (Worthington) surface extends into the Cumberland surface in the center of the Manchester quadrangle at an elevation of 1,500 feet. The Cumberland surface continues across the northern third of the Cumberland Gap quadrangle at 1,900–2,000 feet. Southward some reduced portions of the Upland peneplain are present at elevations of 2,300–2,400 feet. These are followed southward by summit areas of the Log Mountains and Cumberland Mountain at 3,000–3,300 feet above sea level. At the juncture of the Cumberland surface and reduced remnants of the Upland peneplain, a long strath of the Cumberland surface, at an elevation of about 2,000 feet, extends into the reduced Upland remnants. The Upland peneplain, or reduced portions of it which are higher than the Cumberland surface, extends across the southern two-thirds of the Cumberland Gap quadrangle.

The projected profile of the Maynardville quadrangle overlaps with the cutouts made of the southern half of the same quadrangle. The interpretation is made with the regional picture in mind, especially the continuation of the surfaces to the south in the nine-quadrangle area of detailed study. The peneplain and two erosion surfaces are present; the minor strath stage is not shown because of mechanical difficulties present in projected profiles, but its existence is demonstrated by field studies. There are remnants of the Upland peneplain, represented by portions of Cumberland Mountain at altitudes of over 2,900 feet, a few peaks of Clinch Mountain at 2,700 feet, and some parts of Lone Mountain at 2,200–2,300 feet above sea level. There are a very few remnants of the Cumberland surface at altitudes of from 1,900 to 2,100 feet. This surface is poorly pre-

[5] "Rock Resistance and Peneplain Expression," *Jour. Geol.*, Vol. XLIII, Part II, No. 8 (1935), p. 1056.

[6] P. 2 of ftn. 1.

[7] "Erosion Surfaces in Eastern and Southern Ohio," *Jour. Geol.*, Vol. XLII (1934), p. 291; p. 1050 of ftn. 5; "Development and Structural Control of Erosion Surfaces," *ibid.*, Vol. XLV (1937), p. 145; "Erosion Surfaces of Western and Central New York," *ibid.*, Vol. XLVI (1938), p. 193.

served on the Maynardville quadrangle and in the Valley and Ridge generally. The Valley surface, named by Wright,[8] is present at an elevation of 1,500–1,600 feet. It is well shown on the southern fourth of the quadrangle and extends northward as a strath below the remnants representing the two higher surfaces.

WARTBURG–MAYNARDVILLE SECTION

In the Wartburg–Maynardville section, as seen from the south (Pl. II, *B*), the Upland peneplain and two erosion surfaces are shown. In the western half of the Wartburg quadrangle the Cumberland surface, forming the top of Cumberland Plateau, is well shown at 1,800–2,000 feet above sea level. Just east of the central part of the Wartburg quadrangle a peak of the Crab Orchard Mountains, representing a reduced portion of the Upland peneplain, rises to an elevation of 2,500 feet. The Upland is present in the eastern part of the Wartburg quadrangle in the Crab Orchard Mountains at elevations of 2,500 to approximately 3,000 feet. When viewed from the north (Pl. II, *A*), the Cumberland surface may be seen continuing below the higher elevations of the reduced Upland peneplain.

On the Briceville quadrangle the Upland peneplain and two erosion surfaces are present. The surfaces are best shown when the profile is viewed from the south (Pl. II, *B*). The crests of the Crab Orchard Mountains at 3,200–3,500 feet above sea level in the western and central parts of the quadrangle represent the Upland peneplain. In the central portion of the quadrangle below the crests of the Crab Orchard Mountains but above the Valley surface there is a strath of the Cumberland surface at 1,700–1,800 feet. Below the Cumberland surface the Valley surface is well shown in the eastern portion of the quadrangle at elevations of 1,200–1,300 feet. A few prominences rise above the Valley surface to an elevation of 1,500 feet. In the central portion of the Briceville quadrangle the Valley surface extends westward as a strath below the level of the Cumberland surface.

The Valley surface, best seen from the south (Pl. II, *B*), extends across the Maynardville quadrangle at 1,600–1,700 feet in altitude. It is present as a strath below the few peaks of Clinch Mountain, with elevations of 2,200–2,500 feet. The higher portions of these peaks represent greatly reduced remnants of the Upland peneplain, and a few peaks at elevations of 1,800–2,000 feet represent the very poorly preserved Cumberland surface.

PIKEVILLE–LOUDON SECTION

On the profiles of the Pikeville quadrangle, best shown when viewed from the south (Pl. II, *B*), the Cumberland surface forms the top of Cumberland Plateau at elevations of 2,000–2,100 feet west of the Sequatchie Valley. The same surface continues across the top of Walden Ridge to the east of Sequatchie Valley, at elevations of 2,000–2,100 feet. Within the Sequatchie Valley, in the central portion of the quadrangle, is a group of hilltops with elevations of about 1,200 feet, which are interpreted as representing the Valley erosion surface.

The profile of the Kingston quadrangle shows the peneplain and the two erosion surfaces. The Cumberland surface extends completely across the quadrangle at elevations of from 1,800 to 2,000 feet. To the west it is present as a strath below the Upland peneplain, and in the east it stands out above the Valley surface. The Valley surface extends completely across

[8] P. 335 of ftn. 1 (1928).

the quadrangle at elevations of from 1,100 to 1,300 feet. Although the Coosa strath, named by Hayes,[9] is difficult to identify on profiles of this type, the flat area between 600 and 700 feet above sea level in the western portion of the Kingston quadrangle may represent this strath.

With the exception of a few ridge-top elevations in the western portion of the quadrangle, which represent monadnocks on the Valley surface, and a few peaks in the extreme eastern portion of the quadrangle, composed of resistant material, the Valley surface extends across the Loudon quadrangle at elevations of 1,100–1,300 feet. This surface is seen to best advantage when the profile is viewed from the north (Pl. II, *A*).

SEWANEE–CLEVELAND SECTION

The Cumberland surface extends across the western three-fourths of the Sewanee quadrangle at elevations of 1,900–2,100 feet. In the eastern quarter of the quadrangle there are some reduced portions of the Upland peneplain at elevations of 2,300–2,400 feet. The hilltops in the Sequatchie Valley at elevations of 1,000–1,100 feet are interpreted as representatives of the Valley surface.

In the western portion of the Chattanooga quadrangle some summit areas rise over 2,400 feet above sea level, especially on the eastern rim of Walden Ridge, overlooking the Sequatchie Valley. These higher areas represent reduced portions of the Upland peneplain, which is better developed farther north. The Cumberland surface extends almost completely across the quadrangle at elevations of 1,900–2,100 feet. In the western part of the Chattanooga quadrangle it may be seen as a strath beneath the higher peneplain. The Valley surface stands out clearly at 1,000–1,200 feet in the central part of the quadrangle as a surface below the Cumberland when seen from the south (Pl. II, *B*).

Below a few scattered peaks of White Oak Mountain in the western part of the Cleveland quadrangle the Valley surface is developed at elevations of 1,000–1,100 feet. This is best shown when the profile is viewed from the north (Pl. II, *A*). To the east the Valley surface continues completely across the quadrangle below the peaks of Beans Mountain and Big Frog Mountain. The latter has peaks rising over 4,300 feet.

The Coosa surface, which is a minor surface or strath, has been mentioned by practically every worker in the southern Appalachians. It can be seen in the field in the form of terraces covered with stream gravels along the major streams and on some of their tributaries between 650 and 700 feet above sea level.

STRATIGRAPHY AND THE EROSION SURFACES

The Upland peneplain is best developed in the highest portions of the Crab Orchard Mountains, which are capped by resistant Pottsville rocks. The Crab Orchard anticline, as pointed out by W. A. Nelson,[10] is the partially eroded extension of the Sequatchie Valley anticline. Nelson states: "The higher mountains occur on the western and the southern ends. On the top of these ridges and in the old wind gaps the strata have dips of 25 to 34 degrees, but on the mountains that lie on the axis of the anticline the strata lie practically flat or have dips of 5 to 10 degrees to the northwest or southeast."

The Cumberland erosion surface is splendidly developed on top of Cumber-

[9] P. 2 of ftn. 1.

[10] "The Southern Tennessee Coal Field," *Tenn. Div. of Geol., Bull. 33-A* (1925), p. 57.

land Plateau and on Walden Ridge. The cap rock consists of sandstones and conglomerates of Pottsville age, which are strongly resistant to weathering and erosion. The Cumberland surface, however, truncates the structures and the rock units, regardless of their resistance (Fig. 3). Nelson[11] points out that, although the structure underlying the Cumberland Plateau is, in general, horizontal, the area is covered by low anticlines, synclines, and domes, which follow one another in confusing succession. The most perfect erosion surface in the area, the Cumberland surface, truncates these structures and the rock units.

The Valley erosion surface is developed on a very complex set of closely folded and faulted anticlines and synclines in the Valley and Ridge Province. The surface is developed on weak rock units, both limestones and shales, and extends up some of the major valleys in the area, especially into the Sequatchie Valley.

The Coosa surface is a strath in the form of gravel-veneered terraces along the major streams of the area. It is developed on weak rock, principally limestone.

CONCLUSIONS

One peneplain, two erosion surfaces, and a minor surface or strath are present in the southern Appalachians, if the present or recent valley floors are excluded. These surfaces from the oldest (highest) to the youngest (lowest) are: (1) Upland peneplain, (2) Cumberland erosion surface, (3) Valley erosion surface, and (4) Coosa strath.

The term "Upland" is used, as it was employed by Cole[12] in the northern Appalachians, for a peneplain which is higher than the Allegheny erosion surface of the northern Appalachians and above the Cumberland erosion surface of the southern Appalachians.

The first erosion surface below the Upland peneplain is called the "Cumberland erosion surface," and the term is used as a correlative of the Allegheny surface of the northern Appalachians, as used by N. M. Fridley and J. P. Nölting, Jr.[13] It is well developed at an altitude of 1,800–2,100 feet on top of the Cumberland Plateau, on resistant strata of Pottsville age.

Below the Cumberland occurs the Valley erosion surface, which occupies the same relative position as the Lexington (Worthington) surface in the northern Appalachians and is regarded as a correlative of it. It is best developed at elevations of from 1,000 to 1,300 feet in the Valley and Ridge Province on a very complex system of closely folded and faulted anticlines and synclines. It is preserved on weak rock, limestone, and shale. The Valley surface rises gradually northward toward the divide area in the New River region.

The Coosa strath, an incomplete surface, is the lowest of the series and is preserved on weak rock along the major streams. The Coosa is regarded as a correlative of the Somerville of New Jersey and the Parker strath of the northern Appalachians.

ACKNOWLEDGMENTS.—The writer gratefully acknowledges his indebtedness to Dr. W. Storrs Cole, of Cornell University, and Dr. P. B. Stockdale, of the University of Tennessee, for their aid during the field work and the preparation of this paper. The Graduate School of Ohio State University granted financial assistance for the field studies and the photography.

[11] *Ibid.*, p. 54.

[12] P. 135 of ftn. 4.

[13] "Peneplains of the Appalachian Plateau," *Jour. Geol.*, Vol. XXXIX (1931), p. 753.

THE INFLUENCE OF GEOLOGIC STRUCTURE ON THE DRAINAGE PATTERN IN NORTHEASTERN MINNESOTA

KARL VER STEEG
College of Wooster, Wooster, Ohio

ABSTRACT

The region is especially interesting from the standpoint of geomorphology. Erosion of monoclinal structure of the Animikie and Keweenawan formations has developed ridges with an asymmetrical profile, known as "sawtooth mountains." The ridge and valley topography in the area underlain by the Rove slate and associated intrusives (dikes and sills) resembles that of the folded Appalachians. The preglacial drainage pattern was trellised.

The Duluth gabbro is banded; those zones composed of minerals less resistant to weathering and erosive agencies underlie the valleys, and the more resistant rocks, such as the "red rock," make up the ridges.

The lakes located on the Saganaga granite are irregular in outline and are not oriented in any particular direction.

The Pleistocene ice sheets produced noteworthy changes in the drainage lines. Numerous glacial lakes now occupy depressions which show striking east-west alignment. Many of the streams are new or have been forced to find new channels. Waterfalls and rapids and postglacial gorges are common.

INTRODUCTION

The features described in this paper lie for the most part within the Gunflint district of the Superior National Forest in northeastern Minnesota, extending from Lake Superior on the south to the Canadian border on the north and east and to the Cook County line on the west.

A study of the map of the area reveals, almost at first glance, a pronounced orientation of the lakes in an east-west direction. This is especially true of the lakes located east of a line running from the western end of Gunflint Lake southward to Brule Lake and Lake Superior. Owing to the banded character of the Duluth gabbro, there is some degree of alignment west of that line. In the region underlain by homogeneous granite and granite gneiss, north of Gunflint Lake, North Lake, and Arrow Lake, there is no pronounced east-west alignment.

It is the purpose of the writer to show the relation of structure and rock composition to the surface features and to determine the late Tertiary drainage for part of the area.

GENERAL SURFACE FEATURES

The area lies within the physiographic province known as the "Superior upland." It is underlain by coarse-grained, homogeneous igneous rocks of Archean and Algonkian age and by banded, alternating weak and resistant, tilted rocks, mainly sediments and lavas of Proterozoic age. The area is an upland cut by broad, open valleys and diversified by monadnocks, which consist mainly of elongate ridges and rounded higher masses. One who has a preconceived notion that the Laurentian upland, of which the region is a part, is a gently rolling surface of little relief, is due for a rude awakening when he views this area with its rough topography. A drive over the Gunflint Trail from Grand Marais northward to Gunflint Lake is over a seemingly endless series of hogbacks or ridges, giving a gigantic washboard effect. These ridges end where the homogeneous Saganaga granite makes its appearance.

In an area of complex structure and diversified rock composition, an erosion

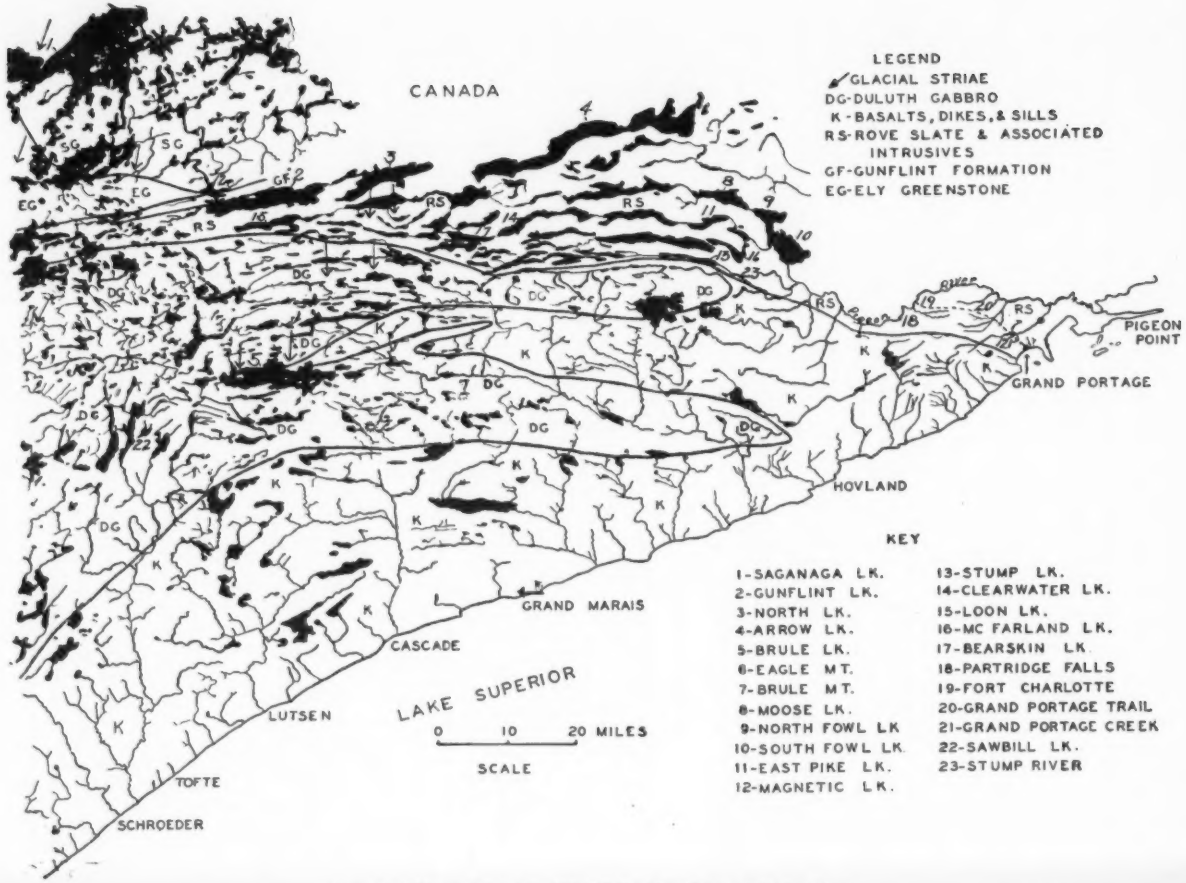


FIG. 1.—Map of area, showing the distribution of the formations

surface may exhibit considerable variation in elevation, being lower on the weaker rocks and higher on the more resistant ones. There is always danger of misinterpreting one erosion surface for many in such a region.

Where the homogeneous, coarse-grained granites, greenstones, schists, and gneisses of Archean age are present, the rolling peneplain shows up to good advantage. In the area of Proterozoic rocks, the Animikian series is composed of the resistant Gunflint iron-bearing formation and the weaker Rove slate. The Keweenawan series includes a great thickness of basalt lava flows, interstratified with sedimentary beds and dipping gently toward Lake Superior to the south.

The Logan diabase sills and dikes intrude the Keweenawan flows and older formations. They dip to the south and form ridges where they intruded into weaker rocks, such as the Rove slate. In the western and central portion of the area, the Duluth gabbro lopolith, which was intruded at the base of the Keweenawan flows, forms a broad upland. The banded composition of the gabbro results in a series of minor ridges standing above the peneplain, not so conspicuous as those in the Rove slate region but of considerable relief. They commonly trend in a slightly northeast-southwest or east-west direction. Rounded knobs of more resistant rock, such as the "red rock" in the area of the Duluth gabbro, are perhaps the most conspicuous of the monadnock features. None is of great extent or of great height, and none would be noticeable were it not for the gently rolling character of the surrounding region, although, in general, they stand higher than the numerous ridges in the area. Misquah Hill (2,230 feet), in Cook County, is the highest point in Minnesota. Among other conspicuous monadnocks are Eagle Mountain and Brule Mountain.

The skyline appears to be horizontal, most elevations forming a common level at about 1,600–1,700 feet. Many points, 1,700–1,800 feet and higher, stand above the general level, and a few monadnocks reach 2,100–2,300 feet. The long, gentle slopes of the broad, open valleys between the ridges lie between 1,300 and 1,600 feet, the average for the areas on the weaker rocks being about 1,300–1,400 feet. The maximum relief of the peneplain is perhaps 400–500 feet, and the average about 100–200 feet.

The Laurentian peneplain was probably developed in the long period of crustal stability in Mesozoic time. If this theory is correct, the peneplain near the summit of the Laurentian upland is of the same age as the Schooley (Kittatinny) erosion surface, widely developed throughout the whole of the Appalachian and New England provinces. Considerable areas within the Laurentian upland may be parts of the resurrected pre-Cambrian erosion surface, which has been little modified since it was uncovered by erosion. After the development of the summit peneplain and long before the glacial epoch, the region was uplifted. The rejuvenated streams dissected the uplands, and at least one lower erosion surface and possibly more were developed. The upland was deeply dissected, broad valleys were developed, and a complex network of drainage lines was established before the advent of the ice sheets.

Outstanding among the physiographic features of the area are the asymmetrical ridges with the long dip-slope to the south and the steeper northward-facing scarps. A view from the highway, east of Grand Marais and at many other points,

Fig. 1.—Map of area, showing the distribution of the formations

shows a skyline with a sawtooth profile. This is especially true of the hills in the vicinity of Lutsen and Tofte. When viewed at an angle, a single ridge broken by gaps may give the false impression of a series of asymmetrical ridges. A number of ridges in succession give the same effect when viewed from a distance. Hence these hills are referred to as "sawtooth mountains."

STRUCTURAL FEATURES

The general structural trend of the rocks in the region, north of Lake Superior, is about N. 70° E., the alignment of the ridges corresponding with the major structures. The structural alignment in the region of the Rove slate is that of a great curve, with the ridges bending slightly to the southeast, in the vicinity of Moose Lake, North Fowl Lake, South Fowl Lake, Pike Lakes, and McFarland Lake. From there eastward, the ridges bend to the northwest in the area north and northwest of Grand Portage.

The most important structural characteristic of the area is the general dip of the formations to the south toward Lake Superior. Where the dipping beds are of unequal resistance to erosion, they produce hogbacks or cuestas, depending on the degree of inclination. On the rocks of homogeneous character, such as granites, there is no alignment of topographic features or drainage.

ELY GREENSTONE (KEEWATIN)

The Ely greenstone underlies a small section of the area and outcrops a few miles to the west of the narrows between Gunflint and Magnetic lakes. It is largely a chlorite schist and shows structures characteristic of lava flows. The intrusion of the Saganaga granite has altered it to hornblende schist. In general, the Ely greenstone is resistant and forms broad, low, rounded knobs and ridges. Farther west, in the Ely district, it forms prominent hills and ridges trending east-west.

SAGANAGA GRANITE (LAURENTIAN)

The Saganaga granite is a typical batholithic mass and is exposed in an area 15 by 25 miles along the boundary of Minnesota and Ontario. It has been deeply eroded, and its eastern exposures are believed to have been many miles below the surface before erosion began.[1]

The granite is intrusive into the Ely greenstone, which it has altered near the contact. It is composed chiefly of orthoclase, plagioclase, quartz, biotite, and hornblende. The Saganaga Lake granite weathers readily, the abundant feldspar changing chemically to kaolin.

The lakes are numerous and very irregular in outline in the homogeneous granite and without definite alignment. The granite area stands somewhat lower than the Ely greenstone and Duluth gabbro to the south and has a gently rolling peneplaned surface of low relief.

GUNFLINT IRON FORMATION (ANIMIKIE)

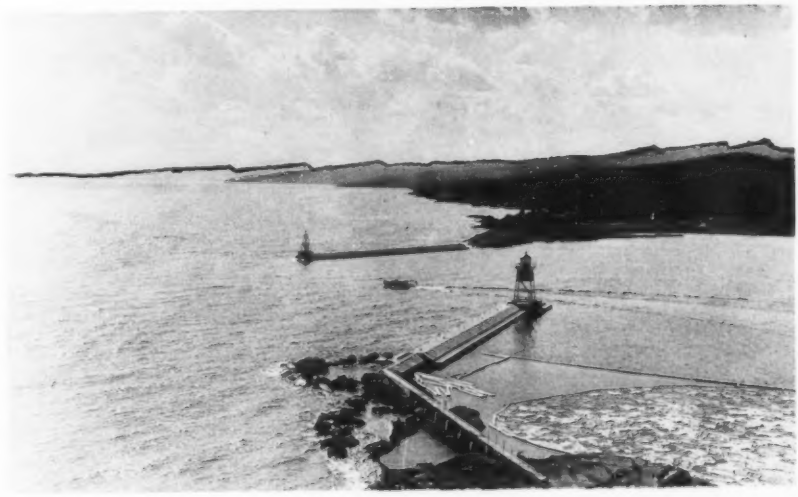
Monoclinal ridges are not restricted to the Keweenawan series. In the Huronian, diabases and quartzites have developed monoclinal ridges with an asymmetrical profile of gentle dip-slopes to the south and steeper faces to the north.

The Gunflint iron-bearing formation of Middle Huronian age is believed to be the equivalent of the Biwabik iron formation of the Mesabi Range. It is from 300 to 700 feet thick in the Gunflint area and may be observed on the north shore and

[1] F. F. Grout, "Structural Features of the Saganaga Granite of Minnesota-Ontario," *Rept. XVI Internat. Geol. Cong.* (Washington, 1933), pp. 255–70; "The Saganaga Granite of Minnesota-Ontario," *Jour. Geol.*, Vol. XXXVII (1929), pp. 562–91.

PLATE I

A



B

A, Carleton Peak, a glaciated monadnock of the Superior upland

B, a view west of the highway near Grand Marais. Note the sawtooth skyline of the Keweenawan basalt flows.

PLATE II

A

B

A, Sea Gull Lake, a typical lake in the Saganaga granite area

B, a typical ridge in the Rove slate area, showing the north-facing escarpment and talus and the dip-slope of a diabase sill. Mountain Lake in the foreground.

PLATE III

Steep north-facing cliffs and gentle southward dip-slopes of the diabase sills overlooking the Rove slate. Note the sawtooth topography of the diabase sills. McFarland Lake, looking west.

to the west of Gunflint Lake. Its outcrop belt trends in an almost east-west direction, parallel with other formations in the Animikie series, which widens in the form of a V to the eastward. The iron formation is exposed only in the vicinity of Gunflint Lake. Increasing amounts of the Rove slate are exposed to the eastward.

ROVE SLATE (UPPER HURONIAN) AND ASSOCIATED INTRUSIVES

The Rove slate received its name from Rove Lake, where it is well developed. The westernmost outcrop of the Rove slate is at the western end of Gunflint Lake; it widens rapidly to the east. The northern boundary of the slate extends northeastward and is limited by the Gunflint iron formation. The Duluth gabbro, which marks its southern boundary, trends east-southeast. The greatest width of the Rove slate in the United States is about 2 miles, and much of this is taken up by sills and dikes, which are intruded into it.

The thickness of the Rove varies, being thinner to the west and thicker to the east on the Canadian side of the boundary, where the larger part of the formation is exposed. A section from Moose Lake to Stump Lake is 3,000 feet thick, composed of about equal amounts of slate and diabase sills. In general, the beds strike about N. 70° E. and commonly have gentle southeast dips, varying from 4° to 15°. Steeper dips and minor folds are present near the Duluth gabbro and other intrusives. Joints are conspicuous and very regular in places. Faults of small throw are present but difficult to trace. They are of little importance in the formation of the conspicuous north-facing slopes.

The structure of the Rove slate is brought into relief by the intrusive dikes and sills, which Grout estimates at about half the volume of the formation.[2] The southward-dipping sills from Gunflint Lake to Stump Lake produce sawtooth mountains with summits regularly spaced. Other sills are present in the area east of Stump River to Pigeon River, but this topography is made more complex by many dikes. The Logan sills stand out as the most prominent topographic features of the region. The high ridges and especially the northward-facing bluffs are, for the most part, composed of intrusive diabase. Exposures are easily reached on the south side of Gunflint, Clearwater, Loon, West Bearskin, and McFarland lakes. Nearly all these lakes and others within the Rove slate area have a scarp or bluff of diabase on the south side. South of Clearwater Lake, for a distance of 3 miles, cliffs of diabase rise to an elevation of 2,000 feet above sea-level and a height of 280–320 feet above lake-level. Many of the northward-facing bluffs contain several sills, which alternate with slate and commonly have a thick sill at the crest.

In the vicinity of Grand Portage and from that locality north and east to Pigeon Point, dikes seem to be more common than sills, but both dikes and sills penetrate the Rove formation throughout the area in Minnesota. The dikes form ridges that are just as conspicuous as the sawtooth mountains formed by the sills, but the dike ridges are different, in that they have a bluff on both sides. The sills are more abundant in the slates, while the dikes are more common in the graywackes and the massive, jointed quartzites. Similar dikes and sills are present in the underlying Gunflint iron formation and in the overlying Keweenawan flows.

[2] F. F. Grout and G. M. Schwartz, "Rove Formation and Associated Intrusives in Northeastern Minnesota," *Bull. Minn. Geol. Surv.* (1933), p. 25.

The diabasic sills of the Rove formation vary from a few feet to more than 500 feet in thickness. A single series of outcrops, indicating a continuous sill, may show a greater thickness of diabase at some points than at others. Many small sills are concealed because the larger ones form prominent ridges, whose talus slopes cover not only the underlying slate but small sills intruded into the slate. Talus accumulations of angular blocks of diabase at the base of the bluffs in many places cover the contact between the diabase and the slate.

TOPOGRAPHY OF THE AREA UNDERLAIN BY THE ROVE SLATE AND ASSOCIATED INTRUSIVES

The topography resulting from the erosion of the weak Rove slate, with its dense diabase sills and dikes, is that of subparallel ridges and broad, open valleys, similar to that of the folded Appalachians, where alternating formations of weak and resistant rocks form parallel ridges and valleys. In the Rove slate area the ridges are not so high as in the Appalachian region; the dips of the beds are lower (5°–10°), and the structure is predominantly monoclinal. The Rove slate topography has developed on a huge monocline, which dips south toward the Lake Superior Basin and once formed the southern flank of a mountain range.

The valleys located on the Rove slate are now occupied by an east-west series of beautiful glacial lakes. The preglacial streams have been greatly modified by glaciation. Transverse valleys are not numerous, but some have important effects on the drainage. The ridges rise to as much as 2,100 feet above sea-level north of Clearwater Lake. Others rise to 2,000 feet, and many stand between 1,800 and 1,880 feet. Where they are highest, the ridges average about 1,850 feet. Farther east, nearer Grand Portage, the ridges have lower elevations, ranging from 1,400 to 1,720 feet. Where the Duluth gabbro upland region bounds the Rove area on the south, its elevations correspond to the highest ridges in the latter.

The lowlands on the Rove slate are at elevations varying from 895 to 1,850 feet, as indicated by the lake levels; but, as some of the lakes are deep, the valleys in which they lie must have been cut still lower. It is reported that many of the east-west–trending lakes are deepest near the south side, a condition to be expected with the existing monoclinal structure. The average elevation of the valley bottoms is not far from 1,650 feet; the average relief is about 200 feet. In general, the elevation of ridges and lowlands decreases as one approaches Grand Portage.

Figure 2 shows the drainage as it probably was in late Tertiary time. The pattern resembles that of the Appalachian Ridge and Valley Province. Windgaps and watergaps were present, although not so large or numerous as in the Appalachians. Doubtless, the drainage was thoroughly adjusted to the structure in the late stage of the cycle of erosion.

It is presumed that the preglacial streams in the parallel valleys on the weak slate drained eastward through the broad, open valley from South Fowl Lake and also along the wide lowland now occupied by Stump and Pigeon rivers, to a point west of Partridge Falls and thence continued in a southeasterly direction. Another possible route for the preglacial waters would be from the ancient valley above Partridge Falls, following the valley eastward from the site of Fort Charlotte along the route now followed by the Grand Portage trail (Fig. 3). The broad open gaps in the dia-

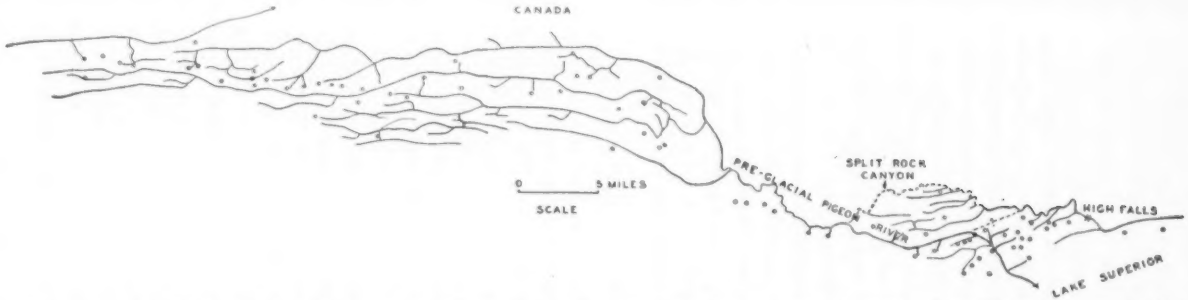


FIG. 2.—Diagram showing preglacial drainage pattern in the Rove slate area. Dashed line represents the portion of the Pigeon River which shifted as a result of glaciation. The circles indicate the location of gaps.

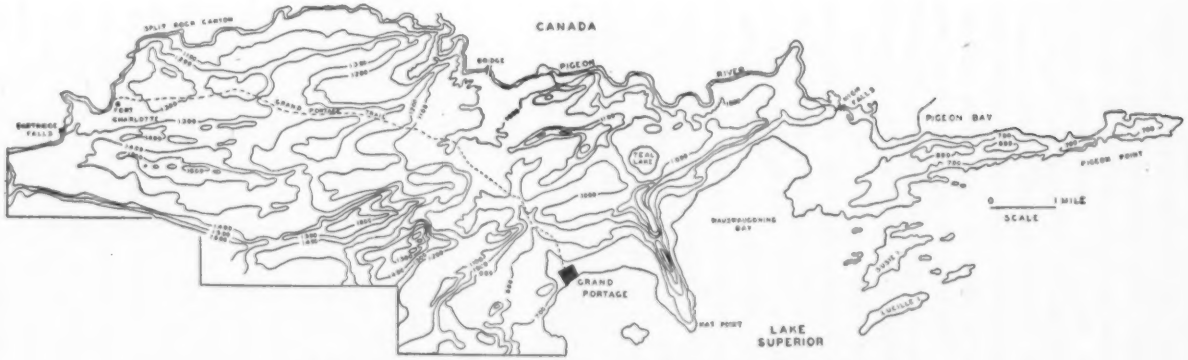


FIG. 3.—Map showing the topography in the vicinity of the Grand Portage

base ridges back of Grand Portage are now occupied by a small stream—Grand Portage Creek—and were doubtless cut in preglacial time by a river considerably larger than the creek now passing through them. Whether the preglacial stream was one of small drainage area or carried the waters from an extensive land surface to the west is impossible to determine. The gaps in the ridges northwest of Grand Portage are ½ mile wide, and it is probable that a stream of considerable size cut them.

The youthful character and circuitous route of the Pigeon River, across numerous resistant diabase ridges instead of by a more direct course to Lake Superior, can be explained as a result of glaciation. It would seem that a more direct route, parallel to the diabase ridges on the weaker Rove slate, would be the logical course. One could hardly select a more difficult route with more obstacles than the present one.

DULUTH GABBRO (KEWEENAWAN)

The Duluth gabbro lopolith lies between the Rove slate district and the region underlain by the Keweenawan flows and sills. F. F. Grout[3] shows that the Duluth gabbro is composed of an alternation of mineralogically unlike bands, accompanied by a fluxion structure and in some places by sheet jointing. Some of the layers, especially near the bottom, are rich in olivine, which weathers rapidly. The ridges and valleys on the gabbro are the result of differential erosion of the bands composed of more easily weathered minerals and belts of more resistant "red rock," a siliceous differentiation product. The structure of the gabbro turns with the lakes from Brule Lake southwestward to Sawbill Lake. This linear adjustment of the drainage lines to the structure is not, however, so well marked in all parts of the gabbro area, especially not in the area to the southwest of Gunflint Lake.

The Duluth gabbro upland, standing well above the Rove slate lowlands to the north, forms a definite escarpment at the contact with that formation. The topography on the gabbro is that of an undulating plain, below 1,000 feet altitude, for the most part. The region is one of low relief, but steep-sided rock hills and vertical escarpments of 10–20 feet in height are very common and well shown along the Gunflint Trail. The sharp hogbacks of low elevation occur so abundantly as to give a washboard effect. The glacial lakes, none of them very deep, cover a considerable portion of the area.

EFFECTS OF GLACIATION

Glacial erosion has been vigorous; in fact, the entire region was pre-eminently one of glacial scour. The hills are almost without glacial debris, and the valleys contain very little, compared with morainal areas farther south in Minnesota, Wisconsin, and Michigan. The topography is one developed by river sculpture, modified by vigorous glacial erosion and some deposition. Characteristic of the area are the expanses of bare rock scoured by glacial action and the thinness of the soil, which, over large areas, is composed of only a veneer of decayed vegetation, such as a mat of moss and pine needles, or of bouldery, infertile transported material. A striking feature is the almost complete absence of any local or residual soil, such as one would expect on a peneplaned surface of low relief.

The drainage of the region is imperfect. The numerous lakes, swamps, waterfalls, and rapids are features of im-

[3] "A Type of Igneous Differentiation," *Jour. Geol.*, Vol. XXVI (1918), pp. 626–58.

mature drainage. The ice sheets removed the residual soil from the peneplain and brought in a thin, bouldery soil, scoured the ledges bare, and displaced the stream courses from the zones of weaker rocks, producing many waterfalls and rapids. The subsequent longitudinal valleys were clogged by glacial drift, thus forming one type of lakes, while those valleys which were deepened by scour produced another type.

The ice came from almost due north, crossing the ridges at a high angle. Thus parallel valleys were not deepened very much, although in many places glacial scour has made rock basins.

In the Saganaga granite area, numerous rounded, deeply grooved or smoothly scoured, domelike or elongate *roche moutonnée* forms have been developed. The same effect is evident on the monoclinal diabase-sill and dike ridges.

Somewhere in their courses, most of the streams in the region exhibit rapids, waterfalls, and narrow gorges; and doubtless there are streams which are entirely new since the ice age. The length, depth, and width of the postglacial gorges are testimonials to the rapidity of erosion since the recession of the ice sheet. The valley of the Pigeon River below Partridge Falls, with its numerous falls, rapids, and deep narrow gorges, indicates that its present lower course is probably a recent one, a result of its diversion by the ice from a shorter course to the south in preglacial time. It is possible that the preglacial Pigeon River drained through one of the broad, open valleys farther south. The writer, however, has also suggested other possible routes during preglacial time.

ACKNOWLEDGMENTS.—The field work was carried out during the summer of 1946 under a grant from the Robert Wilson Research Fund at the College of Wooster. The writer is indebted to Dr. F. F. Grout and Dr. G. M. Schwartz, of the Minnesota Geological Survey, for information and the loan of manuscripts.

A TENTATIVE CLASSIFICATION OF THE MAIN STRUCTURAL UNITS OF THE ANATOLIAN OROGENIC BELT

S. W. TROMP
University of Leiden, The Netherlands

ABSTRACT

A brief summary has been given, in five tables, of the main structural and stratigraphic units of the Anatolian orogenic belt and their possible continuation in southern Europe (the Balkans and northern Italy), based on the author's field observations in the Lombardic Alps (1929–31), Egypt (1937–40), Syria and Palestine (1943), and Turkey (1940–42) and on further evidence from the literature. The main clue to this comparative analysis of regional tectonic units in southeastern Europe and Asia Minor was obtained from a study of the boundary between the so-called "Arabian and Anatolian facies" in southern Turkey and the location of a regional fault zone in northern Turkey, the "Izmit-Erzurum line" (comparable with the San Andreas fault in California), containing the epicenters of devastating earthquakes. Stratigraphical and structural evidence indicate the continuation of this fault zone through the Struma and Morava valleys of the Balkans into the "Drauzug" of the Karawanken Mountains and the Insubric fault zone of the Val Tellina (northern Italy).

INTRODUCTION

There have been several attempts to make a geotectonic analysis of Turkey and neighboring areas, but practically all these studies have been based on scattered geological data published in different articles by geologists who visited Turkey for only a short period. If we realize that even now, after a more or less systematic geological mapping of the country by the *Maden Tetkik ve Arama Enstitüsü* during the last five years, the greater part is still only superficially known, it seems probable that none of these analyses can withstand serious criticism. Turkey is an extremely large country (about 450 km. wide and about 1,500 km. long) with a great variety of most complex stratigraphical and structural problems which can be solved only after years of careful mapping and drilling.

The first structural analysis based on personal observations covering a period of several years was published by P. Arni in 1939.[1] A comparable analysis was published later by Professor W. Salomon-Calvi.[2] Since the publication of these articles, a great number of new data have been collected during exploration work by the Petroleum Department of M.T.A. Enstitüsü, under the leadership of Mr. Cevat Tamşan. Besides surface studies, several deep wells were drilled, which greatly helped to solve certain stratigraphical problems of southeastern Turkey. The writer, who has worked for the Petroleum Department since 1940 both as subsurface geologist and as micropaleontologist, has had the opportunity of visiting many parts of Turkey and of comparing the published data with his own field observations. The following tentative classification of the main structural units of the Anatolian orogenic belt represents a compilation of the data available at present. Undoubtedly, as more information accumulates, changes will be necessary, but our present knowledge makes it rather probable that the main outline will stand. It is for this reason that we have the courage to publish this tentative classification.

[1] "Tektonische Grundzüge Ost-Anatoliens und benachbarter Gebiete," *Maden Tetkik ve Arama Enstitüsü Publication*, Ser. B., No. 4 (1939).

[2] "Kurze Übersicht über den tektonischen Bau Anatoliens," *Maden Tetkik ve Arama Enstitüsü Publication, Bull. 1940*, pp. 49–52.

DIVISIONS AND THEIR CLASSIFICATION

The Anatolian orogenic belt and neighboring areas can be divided into six main units: From north to south, the Pontic orogen, the central Anatolian plateau, the Toros orogen, the Anatolian-Iranian foredeep, the Arabian plateau, and the Arabian shield. Each of these main structural units can be subdivided into smaller units as follows:

I. Pontic orogen or Pontides (P. Arni, ftn. 1)
  A. Pontic foredeep: Kuban depression, Sea of Asow, etc.
  B. Northern Pontic geanticline: central Caucasus, Crimea, etc.
  C. Southern Caucasian trough: Baku-Batum depression, Black Sea, southern Caspian Sea, etc.
  D. Southern Pontic geanticline: northeastern Thrace, Black Sea coastal area, in many places with thrusting toward the north, areas south of the Caspian Sea thrusts mainly toward the north
  E. Northern volcanic zone: Alagöz (4,094 m.), Elbrus (5,631 m.), etc.
  F. Northern, Anatolian fault zone (="Tonale linie" of W. Salomon-Calvi or "Paphlagonische Narbe" of E. Nowack)
    Ismit-Erzurum line

II. Central Anatolian plateau or Anatolides (P. Arni, ftn. 1)
  A. Western and northwestern Turkey (="lydisch-karisches Massif" of W. Salomon-Calvi, ftn. 2)
  B. Konya-Kirsehir Massif (="Galatisch-Lykaonisches Massif" of W. Salomon-Calvi, ftn. 2)
  C. Miocene inner basins of Sivas, etc.

III. Toros orogen or Torides (P. Arni, ftn. 1)
  A. Southern volcanic zone: Hasan Dağ (3,258 m.), Melendizdağ, Erciyasdağ (3,916 m., still active about 100 B.C.), Bingöldağ (3,650 m.), Nemrutdağ (2,949 m., still active in 1441), Ararat (5,165 m.), etc. Volcanic rocks mainly andesites and basalts but also trachytes, etc.
  B. Central Toros geanticline
    1. Antalya Toros (=Pamphylic Toros of Blumenthal)
    2. Seydişehir Toros
      a) Suitandağ
      b) Eğridir-Akseki zone (Seytandağ, Küpedağ, Karakuşdağ, and the southeastern continuation=Imbaros Toros); zone with complicated imbricated structures, all thrust toward the northeast; main serpentine intrusions are Paleozoic
    3. Seyhan Toros
      a) Bulgar-Aladağ zone (=Central Toros or "Kappodokian Toros" of Blumenthal)
      b) Mountains northwest of Seyhan Nehri (=Kilikian Toros); zone with mainly large vertical movements; main serpentine intrusions at the end of the Turonian
    4. Hekimhan-Divrik Toros
      a) Zone with pre-Turonian serpentine intrusions; Middle Eocene syenite and granodiorite intrusions
      b) Ergani Toros: zone with post-Cretaceous serpentine intrusions
    5. Van Toros
      a) Zone with complicated imbricated structures east and south of Lake Van, partly thrust toward the north; many Senonian intrusions
      b) Bitlis-Hakkari Toros (=part of the Iranides of Arni); zone with complicated imbricated structures in the west, small nappe-overthrusts in the east, and all directed toward the south; main serpentine intrusions at the end of the Turonian
  C. Antalya-Adana-Diyarbakir troughs
  D. Southern Toros geanticline
    1. Cyprus (=Trodos complex)—Hatay Toroş (Kizildağ and Gavurdağ="Amanos" of previous authors)—Maraş (=Pyramian Toros) zone; large-scale serpentine intrusions in pre-Turonian time
    2. Siirt-Mardin-Beytuşşebap zone; anticlinal block structures, partly thrust toward the south, separated by large longitudinal fault zones
    3. Zagros range (in Iraq). The Kilikian Toros and Pyramian Toros together are also called "Anti-Toros"

E. Boundary between Arabian and Anatolian facies, often accompanied by a steep folded zone or by longitudinal faults with large-scale basalt extrusions.

IV. Anatolian-Iranian foredeep
- A. Mesopotamian foredeep: Musul-Cizre-Nusaybin-Urfa-Gaziantep zone; near Musul most anticlines asymmetric with steep flank on southwestern side
- B. Gebel Sincar geanticline: Gebel Sincar-Abdul Aziz zone

V. Arabian plateau: Region south of the Gebel Sincar geanticline as far as the Egma Plateau in southern Sinai; many block folded structures and regional graben zones in an over 2,000-m.-thick Mesozoic-Tertiary section

VI. Arabian shield

The writer had intended to indicate these different zones on a map showing their relation to the structural lines of Greece, Bulgaria, Syria, Iraq, and Iran. But as so many problems are still unsolved and particularly as the boundaries between the different units are known accurately in only a few cases, he finally thought it better not to present such a map. Too many maps have been published already on the geotectonics of this part of the world which have been copied in textbooks without further consideration.

A detailed description of each of the above-mentioned units is beyond the scope of this article, especially as a tectonic analysis of each zone should be preceded by a stratigraphical analysis. To provide some of the necessary information, we have prepared five stratigraphic tables (Pls. I–V) giving the main lithologic characteristics of those areas which have been recently studied in detail. These tables also indicate which areas in Turkey are rather well known and which ones require more detailed studies. The vertical distances in the stratigraphic tables were made in accordance with the absolute time scale. From the tables the differences in rate of sedimentation in the different periods can easily be deduced.

The classification of the different tectonic units and particularly the boundaries between them are based mainly on two fundamental structural lines in Turkey which have been studied in detail during recent years—the so-called "Izmit-Erzurum line" and "the boundary between the Anatolian and Arabian facies." As the exact position of these lines is of fundamental importance in understanding the geotectonic structure of Turkey, it is necessary to discuss each of them in detail.

THE BOUNDARY BETWEEN ARABIAN AND ANATOLIAN FACIES

In the Upper Cretaceous and Eocene sections of southern Turkey two facies can be distinguished: a northern facies composed of gray or dark-gray marls, which the writer has called the "Anatolian facies"; and a southern facies, composed of glaring white chalks, chalky marls, chalky limestones, etc., to which we have given the name of "Arabian facies" because a similar facies is known from Syria, Palestine, and Egypt. The boundary between these was accurately established by field studies in the Urfa and Gaziantep region by I. Ortynski and V. Stchepinsky. This facies boundary and the microfaunal characteristics of the Arabian facies have been described recently in an article by Tromp.[3]

The boundary between Arabian and Anatolian facies is mostly located along a steeply folded zone or by longitudinal faults, accompanied in many places by extensive basalt extrusions. This indicates that the boundary is due to a tec-

[3] "Micro-faunas of the Upper Cretaceous and Tertiary Sections (Arabian Facies) in the Urfa and Gaziantep Regions," *Maden Tetkik ve Arama Enstitüsü Publication, Bull. No. 8* (1943), pp. 134–41.

tonic cause. As explained in the above-mentioned article, a notable difference in open-sea conditions, which involved more than a difference in depth of the sea, must have developed during Upper Cretaceous and Eocene times between southern Turkey and the areas farther north.

The well-marked boundary runs in southeastern Turkey almost east-west along the steep mountain front, north and northeast of Cizre, along Mardin southwest of Derik, whence it swings toward the northwest, runs east of the line Viranşehir-Siverek, swings north of Siverek to the west, and goes from there north of Adiyaman toward the southwest, just west of Burç (18 km. west of Gaziantep) and west of Kilis into Syria.

The areas south of this boundary roughly coincide with the northern part of the so-called "Arabian shield," as we pointed out in the above-mentioned article. This name, however, is not strictly correct, as in northern Egypt, Palestine, and Syria a Mesozoic and Tertiary section of over 2,000 m. was deposited on old Paleozoic rocks and was steeply folded into dome-shaped structures. The whole area has, therefore, more the characteristics of a geosynclinal region than of a shield; but because, on the other hand, these areas reacted rather rigidly against tectonic forces (compared with Turkey), we proposed the name "Arabian plateau" for this region, which, still farther south (from the southern part of the Sinai peninsula toward Arabia), passes into the real "Arabian shield" of dominantly pre-Cambrian rocks.

However, the areas south of the facies boundary, in southern Turkey, do not all belong to the Arabian plateau. Immediately south lies a deep basin with a thick sedimentary section, which, except for the Upper Cretaceous and Eocene, does not differ fundamentally from that farther north. It is a zone with many anticlinal structures, particularly in Iraq and vicinity, where they are rich in oil seepages. The whole oil-field belt of Iraq, with the Mesopotamian depression, belongs to this zone. It continues through the Persian Gulf, south of Iran, into the Indus and Ganges depression south of the Himalayan mountains. From there it runs west of Burma, probably along the Andaman and Nicobar islands, toward the islands west of Sumatra. Farther eastward it follows the zone with earthquake epicenters and large negative anomalies south of Java. These large negative anomalies all along this zone in the Indian Ocean (discovered by F. A. Vening Meinesz), their continuation in the so-called "Plumb line" in India (also with large negative anomalies), and the presence of many earthquake centers indicate that great parts of this zone are still in a stage of upfolding. As this zone, which is generally accepted as the southern foredeep of the Himalayan and Malayan orogenic belt, continues into the Mesopotamian depression, we have called the portion of this belt immediately south of the Anatolian-Arabian facies boundary "the Mesopotamian foredeep." The southern boundary of this foredeep in Syria lies probably at the northern flank of the geanticlinal zone formed by Gebel Abdul Aziz and Gebel Sincar. This geanticline swings toward the southeast, following the west border of the Tigris depression. It is the area south and west of this geanticlinal zone which we have called the real Arabian plateau.

THE IZMIT-ERZURUM LINE

Location of the Fault Zone in Turkey

In northern Anatolia an enormous fault zone occurs, similar to the San Andreas fault zone in California, which di-

A TENTATIVE CLASSIFICATION OF THE STRATIGRAPHICAL UNITS IN THE BEST KNOWN AREAS OF THE ANATOLIAN OROGENETIC BELT

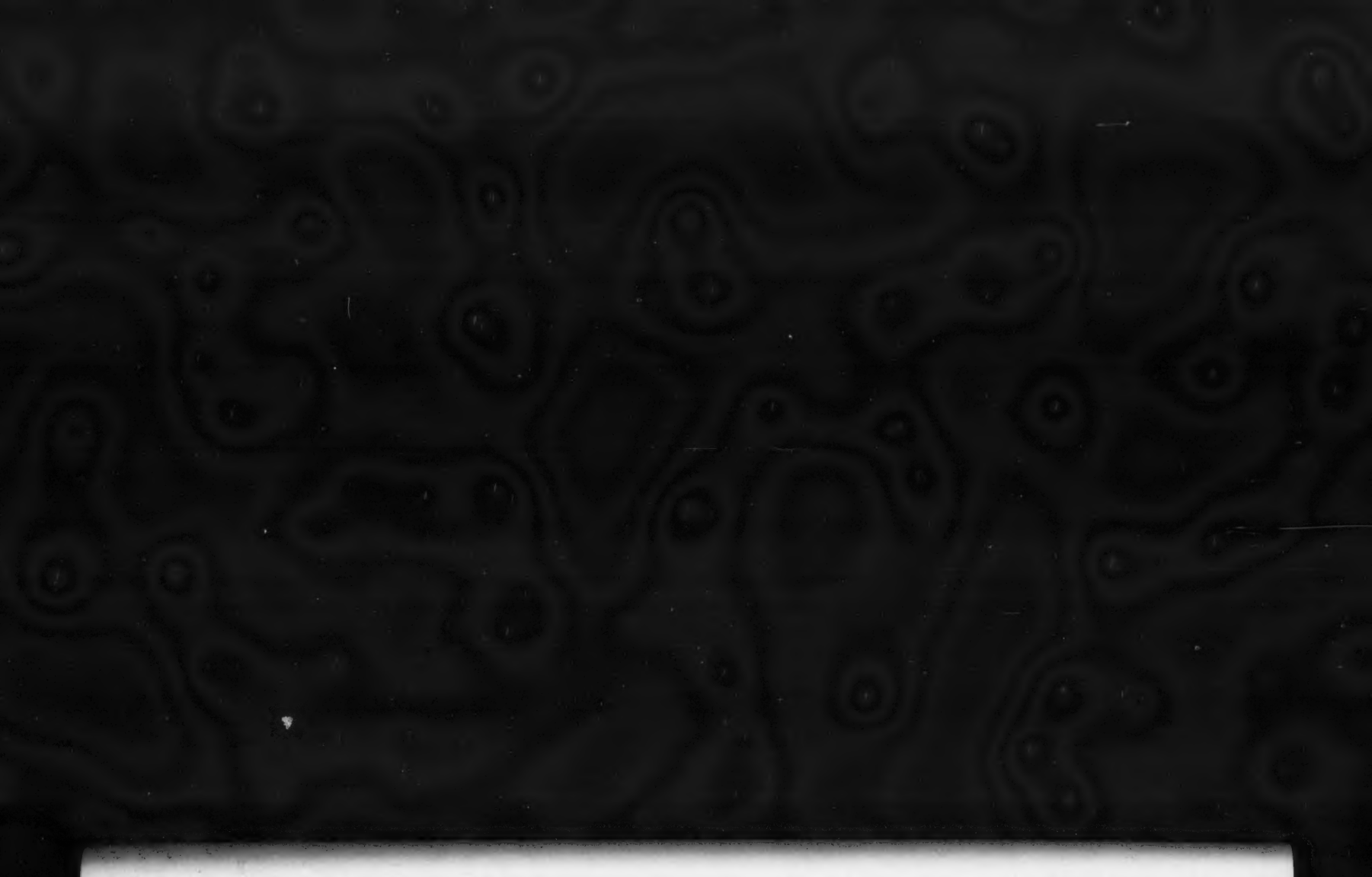
by S W Tromp

I

AGE (vertical distances in accordance with absolute age in million years)				ANATOLIAN-IRANIAN FORE DEEP		SOUTHERN TOROS GEANTICLINE			
				1) Urfa-Gaziantep region		2) SE Turkey (n of Syrian plain)		3) Hatay (s NW Syria)	
				Lithology	Thickness in meters	Lithology	Thickness in meters	Lithology	Thickness in meters
CENOZOIC	QUAT.	PLEISTOCENE (3 MY)		Basalt flows	5-10	Basalt flows	5-10	Basalt flows, thick congl	?
	TERTIARY (58 MY.)	Neogene	Pliocene	Reddish and greenish marls alternating with white porous limestones. Fossils rich in gastropods etc	< 100	Grey, loosely cem. S.S., in lower part calcareous with marly interc., several congl interlayers	> 500	1) Alternation of s.s., marls and congl (with serp. pb.) 2) fg. marls	> 350
			Miocene U	Creamish, reddish and yellow limestones	< 100	Whi l.s. near base altern. of g. gr & s.r. marls and s.s.	> 150	fgr g marls with thin l.s. interc	> 400 ?
			M	Fossils rich in oysters, Pecten, cepidocyclines etc		g. gr & s.r. gyps. marls with l.s. interc.	> 500	fg. marly, near base often changing into l.s	> 300
			L			Whi gypsum with shale int	> 250	Missing	–
		Palaeogene	Oligocene	White, creamish and brownish limestones. Fossils: foss. dyctiocyclines, lepidocyclines, miogypsinoides, lepidocyclina, nummulites, discocyclina, assilina, alveolina, operculina, fasciolites, orbitoides, orbitoclypeus, lepidocyclina, miogypsina, cycloclypeus, heterostegina, amphistegina, rotalia, textularia, miliolina, peneroplis, orbitolites, alveolina, nummulites, discocyclina, assil

AGE (vertical distances in accordance with absolute age in million years)				CENTRAL TOROS GEANTICLINE							
				4) Seydişehir – Toros		5) Seyhan Toros		6) Divrik Toros		7) Bitlis-Hakkari Toros	
				Lithology	Thickness in meters	Lithology	Thickness in meters	Lithology	Thickness in meters	Lithology	Thickness in meters
CENOZOIC	QUAT	PLEISTOCENE (2 MY)		Volcanic tuffs & freshwater lake dep.		Hard conglomerate (igneous pb)	> 600	?	?	conglomerates & Basalt flows	
	TERTIARY (58 MY)	Neogene	Pliocene	Thick tuff deposits, Andesite & trachyte extrusions	?	Missing		?	?	Sds & congl (composed of Permocarb., Cret etc) In upper part andesite & tuff int.	> 1000
			Miocene U	Altern of g marls & Ls serp congl at the base	> 100	Altern of g marls & Ls (after Adana)	600 - 800	?	?	(only near S. border) (mb) L g gyp & gr marls & Ls	> 450
			Miocene M	Missing	–	g marls with Ls interc	> 100			g. gyp & gr gyps marls	> 500
			Miocene L			Salt + K? with magnesit interc.	1000 - 1800			Missing	–
						Ls marls with thin Ls int	2400				
						Ls up to bd Ls & congl	1300 - 2400	Basaltcongl with Syenite bld			
						g limestone	100 - 200				
		Palaeogene	Oligocene	Missing	–	Eocemis Clay series 1) g & gr g sandy marls with Ls bd 2) Ls and congl (Oligocene missing N of Adana)	> 200	Probably missing	–	Missing	–
			Eocene U	Missing	–	Missing	–	Syenitic & granodioritic intr. Formation of magnesite dep.	?	Missing	–
			Eocene M	Lg-whi Camerina Ls	?	g camerina limestone	?	Ls & thin bd sandy Ls with Camerina etc.	?	whi & limestone rich in Camerina & fossiles etc. Brecciated !	> 100
			Eocene L	Probably missing	–	Probably missing	–	Missing	–	Mz (Cherts Red Beds ? Ls & congl 1 Flysch series Base by gr Ls & marls 1 Facies missing incl by serp	
MESOZOIC	CRETACEOUS (65 MY)	Upper Cretaceous	Senonian	Practically missing at base g Ls with orbitoids	–	Missing or extremely thin	? ? ? ?	Missing	–	(Miocene directly on serp congl) Senonian and rare Red bld conglomerate Large serpentine intr.	?
			Turonian	lg limestones with Tenagodes, Hippurites etc	>100	large gabbroidic intr 1) r & gr thin bd Ls with marl int & r. chert nodules 2) Thick bd lg Ls with Tenagodes	? > 100	g. Rudist-limestone	?	dg unfossiliferous Ls	?
			Cenomanian (+Albian & Aptian)	(only developed near Akşehir) Kbr argillaceous Ls with Gryphea and Exogyra spec	?	whi or g massive dolomitic limestone	> 100	g to b massive dolomitic Ls	?	dg massive dolomitic Ls (?)	?
		Lower Cretaceous		Probably missing small scale serpentine intr.	–	Missing		Missing Large scale basic intr.	–	Probably missing	–
	JURASSIC (32 MY)	Malm		1) Red series (Radiolarite series) Red shales with many r & gr chert 2) Flysch series altern of g sandy Cal shales & marls & mixed Ls	> 200 > 1000 max	Radiolarite series r & whi Ls with r chert altern with gr marls & calc Ls	? few hundred	Thin bd Ls with radiolarite(?) intercalations Age: unknown	?	Missing	–
		Dogger		g massive Ls	> 200	lg limestone (?)	?	?	?		
		Liassic		Flaggy limestone series b thin bd Ls with b shaly marl intercalations	> 250	Probably missing	–				
	TRIASSIC (28 MY)	Upper Triassic		Phyllitic series: micaceous phyllites with many quart int (strongly squeezed in Ecailles)	> 400	Megalodon limestone dg thin bd Ls with megalodon prints (Norian ?)	? > 1000	?	?		
		Middle Triassic		Probably missing	–	?	?	?	?	Missing	–
		Lower Triassic		Probably missing	–	?	?	?	?		

AGE (vertical distances in accordance with absolute age in million years)					8) CENTRAL ANATOLIAN PLATEAU (between Konya Çankiri & Kirşehir)		9) Ilgaz Mts		10) Boyabat - Sinop region		11) Zonguldak region (coastal area between Zonguldak & Cide)		12) Trakia	
					Lithology	Thickness in meters	Lithology	Thickness in meters	Lithology	Thickness in meters	Lithology	Thickness in meters	Lithology	Thickness in meters
CENOZOIC	QUAT	PLEISTOCENE (2 MY)			Volcanic tuffs & freshwater lake dep.			—	Basalt flows	> 10			Basalt flows	?
CENOZOIC	TERTIARY (58 MY)	Neogene	Pliocene		Thick tuff deposits Andesite & basalt extr.		Missing	—	Missing	—	Missing	—	r, ge & br soft ss with clay intercalations (Central Thrace) or congl. & ss with Orassensia etc. (S.W. Thrace)	?
CENOZOIC	TERTIARY (58 MY)	Neogene	Miocene	U	Marls with gypsum (Main Lower Gypsum)	In E Turkey ?							S.W. Thrace Basin: [illegible]	?
CENOZOIC	TERTIARY (58 MY)	Neogene	Miocene	M	Tuff, tf and marls, siltstone with marl nod.	marine deg. (Lagidorgeyi) >1000	Missing	—	Missing	—	Missing	—	[illegible]	
CENOZOIC	TERTIARY (58 MY)	Neogene	Miocene	L	Probably missing (Ss)	Limnopyrania —							Probably missing	—
CENOZOIC	TERTIARY (58 MY)	Palaeogene	Oligocene		Tuffitic series (ape unkonformity Kastamonu Basin) 1) salt (the base thick rocksalt dep. Çankiri basin) 2) pal. Clay, 3) s with many lignite beds	> 400 > 50	Missing (present in Kastamonu - Boyabat depression further n)	—	a-3 m thick gr clay bd with g m thick congl. incl. (ab of serp. & Eocene) & s.	> 200	Missing	—	1) Sandstone and shale with coal seams and few volcanic tuff inters. 2) & s with d thin bd partly cherty, shale int., few congl.	> 1000 ?
CENOZOIC	TERTIARY (58 MY)	Palaeogene	Eocene	U	Massive ss with g r-brn/ marl interval. marly, fossiliferous	> 200	Missing (present in Kastamonu basin)	—	Discocyclina s.l. and gr-grey marls	> 25 400	Missing	—	r, g silicic marly & marls, marly & s with inters. of volcanics	> 180
CENOZOIC	TERTIARY (58 MY)	Palaeogene	Eocene	M	Nummulitic ss & marl with more mar.	400	Cemerina & s.	?	Nummulites sp. & Alveolina sp.	> 2000	Missing	—	partly Cemerina & s	> 200
CENOZOIC	TERTIARY (58 MY)	Palaeogene	Eocene	L	Fossiliferous limestone & s.	5 - 25	Missing	—	Cemerina & s. with marls at base	> 100	Missing	—	g silic. shale & s. with melaph. pk etc.	> 130
CENOZOIC	TERTIARY (58 MY)	Palaeogene	Eocene		Probably missing				Missing	—	Missing	—	g silt, shale & s. partly & and g metamorphic overlain by modern alluvia	> 130
MESOZOIC	CRETACEOUS (65 MY)	Upper Cretaceous	Senonian		Practically missing Near Kadışar: b-g marls and ss with Hippurites interval	> 50	Practically missing Sandy & s., marls and calc. ss. (Fossils: Inoceramus (Cripsidia))	? thin	Practically missing calc. ss (of covering basement) or dg. marls with & s. interc. (Inoceramus etc.)	— < 50	marls, ss & gr. marly & s. with inters. of andesites Fossils Inoceramus etc.	few hundred	Mostly missing & s. marl with basalt and andesite interpolations Fossils: Inoceramus etc.	?
MESOZOIC	CRETACEOUS (65 MY)	Upper Cretaceous	Turonian		1) Sandy & s. with orbitoids (age unknown) 2) white massive & s. with Rudists (E of Ishaklip)	?	g. Hippurite limestone Fossils: Rudists, Actaeonella	?	g. white hippurite & s. (massive)	> 50	? congl. of large Cerk. bld. & ss. Cret. pb.	?	Mostly missing Hippurite limestone conglomerate at base (overlaying Eocene or Pressen)	?
MESOZOIC	CRETACEOUS (65 MY)	Upper Cretaceous	Cenomanian (+Albian & Aptian)		Ss, marls & congl. with inters. of andesites, porfyrites etc. (few Cenom. fossils) (only developed in the most N part)	?	g. limestone Fossils: Caprina	?	g & b. shales with thin ferruginous s.s. interkalations Fossils: Duvalia, Hoplitoplites, Crania etc.	> 250	1) pattern of marl, marly & s. with fine coal beds 2) & g. marls with Hippurites etc. 3) Glauconite s.s. rich in Fossils 4) Quartz ss. 5) & s. with small Rudistids 6) & s. of marly, gr. clay, congl. 7) & s. (rich in Orbitolina)	few hundred 100 - 200 100 200 150 70	Missing	—
MESOZOIC	CRETACEOUS (65 MY)	Lower Cretaceous			Practically missing (locally wh. & g. s. with marl intercalations) Fossils: Duvalia, neocomites serpentine intrusions	—	b-g s. and b. marls (Fossils: Desmoceras, Crioceras spec.) Prob. serpentine intr.	?	1) pattern of g. marl and br. calc. ss (large ripple marks) 2) g. shale with calc. thick ss. interc. (ripple marks) 3) g. & g. marl with & s. int. 4) b. shale with & s. int.	350 180 > 200 > 50	r-g & s. rich in Requienia	abt. 100	Missing	—
MESOZOIC	JURASSIC (38 MY)	Malm			Thin bd & s. with thin g. radiolarite interval Many Belemnite fragm.	?	Probably missing		Missing	—	(Missing near Zonguldak) 1) Thin & thick bd. & s. & oolom. 2) & gr. ss. congl. & sandy clay often directly on Permian	600 20 - 200	Missing	—
MESOZOIC	JURASSIC (38 MY)	Dogger			1) & s. with ammonites 2) Marls with Pseudocomya 3) gr. & s. with ammonites	?	g. & s. with & hard shale interc., few ammonites	?	Missing	—	(Missing near Zonguldak) 1) gr. & b-gr. sandy clay, & ss. (with traces of lignite) 2) & clay, & gr. & red. marls, ss.	200 - 300 100 - 150	Missing	—
MESOZOIC	JURASSIC (38 MY)	Liassic			Red & s. rich in ammonites & r. shaly & s. at base congl.	?	Probably missing	—	Missing	—	(Missing near Zonguldak) 1) ss. & sandy clay (with lignite) 2) gr. & r. mil clay & marl	300	Missing	—
MESOZOIC	TRIASSIC (28 MY)	Upper Triassic			Strongly recrystl. l-g & & massive & s., rich in gastropods (prob. Ladinian)	? (thin)	Missing	—	Missing	—	Missing	—	Missing, only developed E of Bosphorus Rhetian - Norian: missing Carnian Ladinian Anisian } massive & s. Werfenian: { sandy marl & s. etc. congl.	?
MESOZOIC	TRIASSIC (28 MY)	Middle Triassic												
MESOZOIC	TRIASSIC (28 MY)	Lower Triassic												



AGE (vert. distances in accordance with absolute age in million years)		ANATOLIAN-IRANIAN FORE-DEEP		SOUTHERN TOROS GEANTICLINE				C
		1) Urfa-Gaziantep region		2) S.E. Turkey (n. of Syrian plain)		3) Hatay (& N.W. Syria)		4) Seyc
		Lithology	Thickness in meters	Lithology	Thickness in meters	Lithology	Thickness in meters	Lith
PALAEOZOIC	PERMIAN (34 M.Y.)	?	?	Giridağ series: r. br. quartzites gr. argillites b. limestones (Age: uncertain, pre-Goyan series, probably post carb.)	> 430 75 > 30	Probably main period of serpentine intrusion (many chromium dep.) Acc. to Dubertret a.o. age of intrusion U. Cret.	—	1) Reddi s.s. and sed of quartz 2) Large mass
	CARBONIFEROUS (86 M.Y.) Upper Carb.	?	?	Harbol series: exact age unknown Black limestones with Productidae and Fusulinidae In lower part alt. with b. shales and ye. br. quartzites.	> 250	Missing	—	dg. or and pr
	CARBONIFEROUS (86 M.Y.) Lower Carb.			?	?			
	DEVONIAN (45 M.Y.)	?	?	Probably missing	—	Missing	—	Black
	SILURIAN (94 M.Y.)	?	?	Probably missing	—	?	?	
						Gavurdağ series: Phyllites, marbles & quartzites (intruded later by serpentines) Fossil: Trilobites	?	
	CAMBRIAN (105.000.000 YEARS)	?	?	Telbisim series: (at Derik, W of Mardin) 1) g. thick bd. s.s. 2) g. s.s. and green micaceous shales with Brachiopods and Trilobites 3) d.g. thick bd. dolom. L.s. with many chert concretions 4) Thick bd. r. sandst., in lower part thin bd. and gr. s.s. interc. 5) conglomerate of r. & gr. porphyric p.b.	> 700 40 200 480 40	?	?	
				Volcanic series: red porphyry flows with few "lahar" & lapilli intercalations (Age: uncertain, perhaps Algonkian Proterozoic)	> 800			

NE .		CENTRAL TOROS GEANTIC						
ria)		4) Seydişehir - Toros		5) Seyhan - Toros		6) Divrik - Toros		7) Bi
	Thickness in meters	Lithology	Thickness in meters	Lithology	Thickness in meters	Lithology	Thickness in meters	Li
	—	1) Reddish and greenish s.s. and congl., composed of serpentine ph. quartz etc. 2) Large serpentine massive	> 20	Dark grey Fusulinidae limestone	?	?	?	Proc d.g.
	—	d.g. or b. fusulina and productidae L.s.	> 100	Black limestones with few b. shale intercalations. Fossils: Fusulinidae; rich in Brachiopods (Productidae, Spiriferidae)	several hundred	?	?	1) Bl ma in 2) Al gr. l r. sh
		?	?	?				
	—	Black coral L.s	?	1) Alternation of br. & b. Spirifer limestone Fossils: Brachiopods; Corals 2) Br. calcareous s.s. and sandy L.s.	probably few hundred	?	?	Prot
	?	?	?	?	?	?	?	
	?	?	?	Niğde series: whi. marbles, many quartzites, phyllites, micaschists, gneiss, amphibolites etc. (Age: uncertain, but pre-Devonian)	?	?	?	Per mic tes,(amp (Age pre
	?	?	?	?	?	?	?	

T I C L I N E		
	7) Bitlis-Hakkari-Toros	
hickness n meters	Lithology	Thickness in meters
?	*Practically missing* *d.g. or b. fusulina L.s.*	?
?	*1) Black massive L.s. or marbles, often rich in fusulinidae* *2) Alternation of r. & gr. thin bd. L.s. with r. shaly intercal.* ?	> 100 50 ?
?	*Probably missing*	—
?	?	?
?	*Pervari series:* *micaschists, quartzites, (often ferruginous) amphibolite intrusions* *(Age: uncertain, but pre-Carboniferous)*	?
?	?	?

AGE (vert. distances in accordance with absolute age in million years)		CENTRAL ANATOLIAN 8) PLATEAU (between Konya, Çankiri & Kirşehir)		SOUTHERN PONTIC GEANTICLINE							
				9) Ilgaz Mts.		10) Boyabat-Sinop region		11) Zonguldak region (coastal area between Zonguldak & Cide)		12) Trakia	
		Lithology	Thickness in meters	Lithology	Thickness in meters	Lithology	Thickness in meters	Lithology	Thickness in meters	Lithology	Thickness in meters
PALAEOZOIC	PERMIAN (30 M.Y.)	Probably serp. intr. Practically missing 1) s.s. & congl. with b. L.s. ph. 2) dg. or b. L.s., with Neoschwagerina, Sumatrina etc.	thin	Serpentine intrusions in schists, age unknown	—	Probably missing		1) r. & ye. s.s. 2) r. sandy clay with s.s. int. 3) r. sye. felspar s.s. (arkose) 4) r. clay and s.s. with raindrop prints Fossils: Walchia 5) whi. s.s. and fine congl. with r. interlayers 6) congl. of huge L.s. bd.	> 1000 (acc. to Grancy)	Missing	—
	CARBONIFEROUS (86 M.Y.) Upper Carb.	1) b. calcite veined limestones, mostly unfossiliferous (Schwagerina L.s.) 2) Sandstones, congl. & schists, with thin intercalations of b. limestone Fossils: very rare (Productidae, Spiriferidae)	? (prob. thick)	Probably missing	—	Probably missing	—	L. Namurian (? Visean): Zonguldak series: 1) congl. s.s. with clay-slate & coal int. Two facies: Facies of N facies: many int. Rilly or S. facies: few int. Kozlu series: congl., congl.-s.s. with clay-slate & coal int. Two facies: Facies of N facies: many int. Rilly or S. facies: few int. Upper Alacaağaç series: clay-slate with many s.s. int. stigmaria fibers, several thick (up to 1 m) coal beds Lower Alacaağaç series: clay-slate with few s.s. int. rarely few coal bd. At base a bauxitic hor. Black limestones with few b. shale intercalations in upper part. Several irregular b. chert beds. Locally r. & gr. colours in L.s. Fossils: Productidae, Zaphrentis etc.	> 200 > 1000 200 100-300 abt. 1000 (perhaps partly Dev.)	Missing	—
	Lower Carb.										
	DEVONIAN (45 M.Y.)	?	?	Probably missing	—	Missing	—	b. phyllites, sandstones and limestones (exact stratigraphy unknown)	?	Thrace series: marine, main calc. graywacke, s.s. few congl. Probably diabasic intr. 1) g. bd. flaggy L.s. nodular L.s. argill. L.s., shaly int. Gazdik series: 1) pelagic facies: nodular L.s., marls & calc. shales Bouma-sequ. facies: L.s. with many graywacke int. 2) Greywacke	several hundred 50 max. 100 > 500		
	SILURIAN (94 M.Y.)	?	?	?	?	?	?	?	?	Gothlandian two facies: Pelagic facies: marine 1) grey quartz. dg. grey mostly arkose 2) g. thick bd. quartzites 3) r. vol. & r. arkose 4) coarse multicol. s.s. congl., arkose & clay Coral L.s. facies: 1) dk. massive L.s. 2) thin bd. g. L.s. with r. & br. marl int. 3) g. partly nodular L.s. rich in Tabulates 4) g. thick bd. L.s. with r. marl int. 5) Tabulate L.s. congl. with cryst. pb.	100-200 100-250 70-150 100 300-400 30-40 100 50 ?		
	CAMBRIAN (105.000.000 YEARS)	Extensive granite & granodiorite intr. (age: uncertain) Hüdde series: white marbles (abundant), mica-garnetschists, quartzites etc. same section also described as Bozdağ series and Kirşehir metam. series (age: uncertain)	?	Ilgaz series: Phyllites, marbles, quartzites, etc. intruded by serpentines (age: uncertain)	?	Diorite intrusions Ilgaz series: chlorite-, talc-, epidote- and muscovite schists. (age: uncertain)	?	?	?	sericite schists, phyllites etc. intruded by granites (age: uncertain, but pre-U. Silurian)	?
		?	?	?	?	?	?	?	?	?	?

vides the mountainous part of Turkey into two large units. This fault zone was called by E. Nowack the "Paphlagonic scar" and the "Tonal line" by W. Salomon-Calvi. The latter, in particular, has written several articles on this fault zone,[4] which he was inclined to consider equivalent to the regional fault zone south of the Alps, called the "Insubric fault zone" by A. Spitz and previously called "Tonal line" by Solomon-Calvi (in 1890). This Insubrian fault zone, considered by Staub and others as the Alpino-Dinaric boundary, was studied in detail by Cornelius and his wife and likewise by the present writer over a considerable distance in northern Italy.[5]

Before considering whether the "Paphlagonic scar" can be the same as the "Insubric fault zone" in Italy, we shall first discuss the characteristics of the northern Anatolian fault zone. This zone comprises a series of parallel thrust faults, which show up topographically in the form of different large depressions ("Ovas"). But most striking is the presence of many earthquake centers all along this zone, which indicate that intermittent movement is still continuing along these faults. The location of these centers of devastating earthquakes, combined with the surface studies of Blumenthal and others, makes it possible to trace this fault zone very accurately. It can be traced with certainty (Fig. 1) through the Gulf of Izmit, along Izmit, Sapança Gölü, south of Adapazari and Hendek, south of Bolu, along the Gerede Çay (south of Arkot Dağ), along the Upper Ulu Su and Devrez Çay, south of the Ilgaz Mountains, along the valley south of Tosya, along the Kizil Irmak depression, via Osmancik, and along the Sulu Ova to Erbaa; thence along the Kelkit Irmak to Niksar, Reşadiye, south of Koyulhisar, north of Suşehri, and north of Refahiye and Erzincan. A cross-fault brings the fault line farther north toward Tercan and Erzurum. From there it continues in a northeast-southwest direction via Hasan Kale (Pasinler), Kağizman to the Aras Graben Valley (north of the Ararat volcano and south of the Alagöz volcano), and along this valley in a southeast direction through Russia into western Iran. As this fault zone lies between the well-known cities of Izmit and Erzurum, it may be designated appropriately as the "Izmit-Erzurum line."

CONTINUATION OF THE FAULT ZONE WEST OF TURKEY

The continuation of this fault zone west of Izmit is not completely certain, but most probably it follows the more than 1,000-m. deep east-west troughs in the Sea of Marmara and crosses the Gallipoli Peninsula into the Gulf of Saros. From there it probably follows the southwest-directed depressions in the sea between Samothrace and Imbros Island. Farther westward it swings to the northwest but is probably cut by a regional northwest-southeast fault zone. This western continuation into Greece is uncertain, and we shall come back to it later after the discussion of the Toros orogen. It is most likely that it runs east of the Vardar Valley in Greece, probably near or in the Struma Valley, and from there in a northwest direction

[4] "Fortsetzung der Tonalelinie in Klein Asien," *Akad. d. Wiss. Wien*, Vol. XVII (June, 1937); ftn. 2; "Untersuchungen über Erdbeben in der Türkei," *Maden Tetkik ve Arama Enstitüsü Publication*, Ser. B, No. 5 (1940).

[5] H. P. Cornelius and M. Furlani-Cornelius, *Die insubrische Linie vom Tessin zum Tonale Pass* (Wien, 1930); S. W. Tromp, *La Géologie du valle del Bitto et la tectonique des Alpes lombardes* (Leyden, 1932); "De Geologie der Bergamasker Alpen in Verband met het Dinaridenprobleem," *Geologie en Mynbouw*, November 16, 1932; "De Genese der lombardische Alpen en die der oost alpine Dekken," *ibid.*, December 16, 1932.

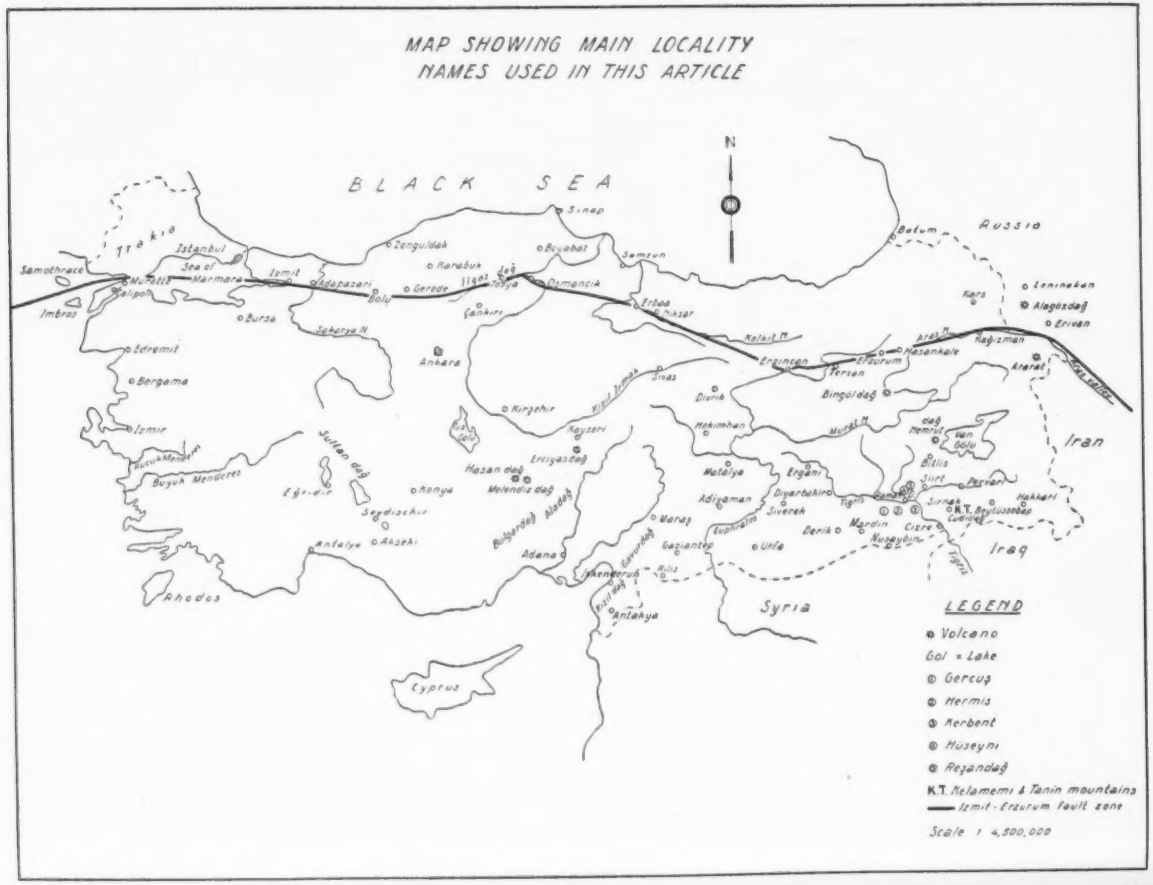

MAP SHOWING MAIN LOCALITY
NAMES USED IN THIS ARTICLE
N
BLACK SEA
Russia
Iran
Iraq
Syria
Cyprus
Rhodes
Samothrace
Imbros
Istanbul
Sea of Marmara
Izmit
Adapazari
Bolu
Gerede
Ilgaz
Tosya
Osmancik
Sinop
Zonguldak
Karabuk
Beyobat
Samsun
Batum
Kars
Leninakan
Alagözdag
Erivan
Erbaa
Tokat
Amasya
Erzincan
Erzurum
Hasankale
Refahiye
Ararat
Bingoldag
Tercan
Divrik
Sivas
Kirsehir
Kizilirmak
Ankara
Kayseri
Hekimhan
Malatya
Ergani
Adiyaman
Diyarbakir
Siverek
Tigris
Bitlis
Van
Van Gölü
Siirt
Derik
Mardin
Cizre
Nusaybin
Urfa
Gaziantep
Maras
Adana
Iskenderun
Antakya
Afsin
Elbistan
Kahramanmaras
Elbistan
Antalya
Alaseh
Seydisehir
Konya
Eregli
Beysehir
Aladag
Hasan dag
Melendiz dag
Erciyasdag
Sultan dag
Buyuk Menderes
Kusadasi
Izmir
Edremit
Bergama
Bursa
Seberya N.
Gelibolu
Gelibolu Pen.
Hakkari
Yüksekova
Semdinli
K.T. Beytüssebap
Cudi dag
K.T. Nelamemi & Tanin mountains
LEGEND
Volcano
Gol = Lake
Gercus
Hermis
Kerbent
Huseyni
Rezandag
Izmit - Erzurum fault zone
Scale 1 4,500,000

FIG. 1

through the Morava Valley in Yugoslavia.

From the main Izmit-Erzincan fault zone, other fault zones branch off in different directions, but they cannot be discussed for lack of space.

AGE OF THE FAULT ZONE

The age of the main fault is probably pre-Cretaceous, as it disappears in places under Cretaceous flysch. The fault zone may have been present even in Paleozoic time. The Insubric fault zone in Italy is along a Paleozoic fault line, on which there was renewed movement during the Tertiary folding.

SUMMARY OF DEVASTATING EARTHQUAKES IN TURKEY

As stated previously, one of the most characteristic features of this fault zone is the occurrence of many destructive earthquakes all along the zone. Between 1939 and 1943 four severe earthquakes took place: at Erzincan (21.XI.1939 at 10 o'clock and 27.XII.1939 at about 2 o'clock); near Osmancik, about 120 km. south of Sinop (at Kargi on 21.XI. 1942, in the Kizil Irmak Valley on 2.XII. 1942, and in the Hamamözu Valley on 11.XII.1942); near Erbaa and Niksar, about 70 km. south of Samsun (20.XII. 1942), and near Adapazari (20.VI.1943 at 18 hr. 33 min. and 19 hr. 48 min.). Hundreds of people were killed during these earthquakes, and thousands of houses were destroyed.

The Erzincan earthquake was followed a few days later by recurring shocks at several places along the Izmit-Erzurum line as far as Mürefte. This is another indication that these different epicenters really belong to the same fault zone. Some portions of this fault zone, which is over 1,500 km. in length, are more active than others. Izmit, for example, has several times been partly or completely destroyed (2.I.69, 24.VIII.358, 2.XII. 362, 16.VIII.555, 25.V.1719, 15.IV.1878, 10.VII.1894); Erzincan has suffered similarly twenty-six times (in 1011, 1045, 1161, 1165, 1166, 1168, 1236, 1251, 1254, 1268, 1281, 1287, 1289, 1290, 1308, 1374, 1422, 1433, 1458, 1482, 1543, 1578, 1584, 1605, 1784, 1939). The Turkish government is now attempting to rebuild the town outside the fault zone and in accordance with the principles of modern earthquake construction developed in Japan and the Dutch East Indies. Erzurum was either completely or in greater part destroyed at least thirteen times (in 1268, 1458, 1482, 1584, 1659, 1794, 1843, 1850, 1852, 1860, 1861, 1901, 1902). Kars (near the Russian frontier), Lenihakan, and Erivan (both in Russia near the Alagözdağ) have been demolished several times, as they lie in the neighborhood of the Aras graben.

In western Turkey, south of the Izmit-Erzurum line, several nearly east-west grabens are probably due to north-south stretch phenomena in the curved part between the Anatolian and Greek orogens. These will be discussed later in greater detail. Here it is sufficient to state that many earthquakes originating in these grabens (the Iznik, Bursa, Endremit, Bergama, Gediz, Izmit, and Kücük Menderes grabens, and the Büyük Menderes graben north of Rhodos) indicate that likewise in this western part of Turkey the upfolding phase of the Anatolian orogenic belt has not yet ended.[6]

The Anatolian orogenic belt is cut near the southern boundary by the north-south Dead Sea graben zone, which continues through Syria, into Turkey

[6] Heavy earthquakes at Dikili in the Bergama graben on 22.IX.1939; destruction of Bergama in 1296; of Izmir in 178 B.C., and A.D. 1056, 1668, etc.

FIG. 1

east of Antakya (Antioche), and east of the Gavurdağ as far as Maraş. This zone is also still active, as is proved by destructive earthquakes in Antakya in 713, 1091, and 1156 and near Maras in 1114.

Unquestionably, the Izmit-Erzurum line is a fault zone of regional importance. It also forms, roughly, the boundary between two different areas, the so-called Pontic orogen to the north and the the central Anatolian plateau (= Anatolides) south of the fault. The different stratigraphic development of the two units can be seen in Table III.

THE CENTRAL ANATOLIAN PLATEAU (ANATOLIDES)

The central Anatolian plateau is a very rigid zone, mainly composed of Paleozoic sediments, schists, and igneous rocks and covered by not very strongly folded Mesozoic sediments. These Anatolides of P. Arni were consolidated during the Hercynian folding, but they subsided again during the Mesozoic. Although the subsidence began in the Triassic, large parts of these high Hercynian mountains were not covered by the sea until late Mesozoic time. The Alpine uplift started first in these central parts. Owing to these two factors, the thinly developed Mesozoic cover was more eroded on this central Anatolian plateau than in the Toros Mountains to the south, and it disappeared completely farther west. During the Tertiary upfolding of the Anatolian orogenic belt the crestal part of this big dome broke and subsided with respect to the flanks. This became the site of a large inland sea during the Oligocene and Miocene, as is evidenced by lagoonal deposits and lignites.

THE PONTIDES

The northern flank of the Anatolian orogenic belt, i.e., the belt north of the plateau, is formed by the Pontides, which are composed of two geanticlinal strips separated by a trough. The southern flank (south of the plateau) is formed by the Torides or Toros orogen. On both sides of the Anatolian orogenic belt we find a foredeep—the Mesopotamian (previously discussed) on the south and the Pontic foredeep, containing the oil fields of the Kuban depression, on the north. The stratigraphic development of the Pontides is treated in Tables III and V.

THE TOROS OROGEN

Between the Toros orogen and the central Anatolian plateau lies a zone with several large volcanoes, some of which were still active in historic times. This volcanic inner zone can be compared with the volcanic inner zone of the Malayan orogen.

MAIN DIRECTIONS OF THRUSTING

The Toros orogen is a very complicated group of mountains with much variation in their stratigraphic and structural features. Thrusting both toward the north and toward the south can be observed. Both were probably caused by movements of the Arabian shield toward the north. If these movements led to thrusting at a high level in the earth's crust, we should find displacements in the younger sediments directed toward the north; but if the compression was more effective at a greater depth, this underthrusting would turn the younger sediments toward the south. Which manifestation took place was determined by the structure of the Arabian shield, the varying resistance in front of the shield, and other factors. The generalization often put forward, particularly by German authors, that the Pontides are folded only toward the north and the

Torides only toward the south is definitely incorrect.

DIFFERENCES IN TIME OF INTRUSION

Also differences in time of serpentine intrusion in the Torides can be observed both in east-west and north-south directions (see section on "Divisions and Their Classification, Toros Orogen"). In the Bitlis-Hakkari region (eastern Turkey) the main intrusion took place at the end of the Turonian and the beginning of the Senonian, whereas immediately south in the Siirt-Beytuşşebap zone no intrusion at all took place in this period. These large-scale serpentine intrusions, which are so characteristic of the Toros orogen, represent the parent-rock for the rich chromium deposits of Turkey.

FOLDING PERIODS

In the central Toros geanticline the first large-scale block movements took place at the end of the Turonian, when most of this area came above sea-level and delivered sediments for the Senonian and Lower Eocene formations of the southern areas, where subsidence continued until the end of the Lower Eocene. Both areas were strongly uplifted in the Middle Eocene, followed by a further subsidence of the southern areas during the Neogene. Most of the Torides, however, remained above sea-level after the Middle Eocene. It was only in the troughs between the central and southern Toros geanticlines that an extremely thick Neogene section could be deposited (see Table II, "Seyhan Toros"); this is one of the thickest known in the world and is not due to duplication of sections by faulting.

The Torides present many other interesting features, but a fuller discussion cannot be given in this article.

POSSIBLE CONTINUATION OF THE ANATOLIAN OROGENIC BELT IN SOUTHEASTERN EUROPE

CONTINUATION OF ANATOLIAN TECTONIC UNITS IN THE BALKANS

Kober, Kossmat, Renz, Philippson, Von Seidlitz, and others have tried to give a geotectonic analysis of the Balkans. However, they have had to face the fact that the geology of the western Balkans is still very poorly known. The author also knows the Balkans, except for a tourist trip, only from studying published articles, thus making any comparison with Turkey largely conjectural. But there are four structural elements or features in Greece which make a comparison between Turkey and Greece still possible. They are as follows:

1. The continuation of the Izmit-Erzurum line
2. The lithology of the Cyclades
3. The situation of the active Santorini volcano and the extinct volcano of Milos
4. The presence of the so-called "eastern Hellenic" and "Vardar" zones of Von Seidlitz in eastern Greece

The westerly continuation of the Izmit-Erzurum fault line has already been considered. As far as the Chalkidikean Peninsula in Greece, there seems to be little doubt about the situation of the fault zone, but whether it enters the Struma Valley or not is an open question.

In eastern Greece and Yugoslavia there are two zones described by Von Seidlitz—the eastern Hellenic zone and the Vardar zone. The eastern Hellenic zone (in the eastern Peloponnesus) is, according to the literature, composed of Paleozoic rocks covered by Triassic and Jurassic beds (with serpentines, gabbro, and diabasic intrusions), which are unconformably overlain by Upper Creta-

ceous strata. The Vardar zone, which lies east of the eastern Hellenic zone, is apparently composed of Paleozoic graywackes, marbles, etc., covered by Triassic and Jurassic beds of abyssic facies with many large basic intrusions (serpentine, etc.), unconformably covered by Upper Cretaceous flysch. P. de Wÿckerslooth[7] has indicated on a map the different chromium deposits of Greece and Yugoslavia, all of which lie in this Vardar zone, with large serpentine intrusions. There seems to be very little doubt that this Vardar zone can be compared with our central Toros geanticline, which has similar large-scale serpentine intrusions, rich chromium deposits, and a similar lithologic development of the Mesozoic.

The Cyclades are composed of metamorphic rocks like those of western Turkey. If we consider the Cyclades as the continuation of the Anatolides and try to connect the Torides via Crete, south of the Cyclades, with eastern Greece, we get a rather simple regional fold bending around a vertical axis.

In the core below the anticlinal crest lie the Cyclades. Between the Cyclades and the continuation of the Torides we find the volcanoes of Milos and Thera (Santorini). This arrangement can be compared with our southern volcanic zone in Turkey between the Torides and the central Anatolian plateau.

The previous discussions make it most plausible that the western continuation of the Izmit-Erzurum line must be east of the Vardar zone (being the continuation of the Toros geanticline) and, according to the serpentine and chromium-ore distribution in Yugoslavia, it should be east of a line which begins near the point of confluence of the Drina and Save, and extends east of the Kopaonik Mountain (west of the Morova Valley), east of Pristina and Skolpje, east of the Vardar Valley, and through the Gulf of Kassandra (western Chalkidike).

East of this Vardar zone in Bulgaria begins the so-called "Rhodope Massif," mainly composed of marbles, schists, and other Paleozoic rocks, similar to western and northwestern Turkey. All these facts make it reasonable to continue our Izmit-Erzurum line through the Rhodope massif, along the Struma and Morava valleys. By adopting this line we may recognize and compare the following zones in the Balkans:

1. The Dalmatian cost and western Peloponnesus, which should represent the southern Toros geanticline.
2. Central Yugoslavia and eastern Greece, representing the central Toros geanticline.
3. The volcanoes of Milos and Thera, representing the southern volcanic zone.
4. The Cyclades and the areas in Greece and Yugoslavia between the Vardar zone and the Morava-Struma Valley should represent the western thinning of the central Anatolian plateau, similar to the eastward thinning east of Sivas in Turkey.
5. The Struma-Morava depression, expressing the Izmit-Erzurum fault zone.
6. The Rhodope massif, comparable to the western crystalline part of the most southern zone of the southern Pontic geanticline, probably continuing with the Balkan Mountains of Bulgaria into the Transylvanian Alps of Rumania.

CONTINUATION OF BALKAN TECTONIC UNITS IN NORTHERN ITALY

The next question is whether we can accept Salomon-Calvi's assumption that

[7] "Die Chromerzprovinzen der Türkei und des Balkans und ihr Verhalten zur Grosstektonik dieser Laender," *Maden Tetkik ve Arama Enstitüsü Publication, Bull. No. 7* (1942).

the Izmit-Erzurum line is the same as his Tonal line of northern Italy. In order to study this possibility, we must summarize the main characteristics of this fault line in the southern Alps.

Proceeding southward from the areas near the Swiss-Italian frontier, which contain the "roots" of the Pennine nappes, we can distinguish the following zones:

1. *Tonal metamorphic zone.*—The Tonal zone comprises phyllites, garnet-staurolite schists, with many marble and amphibolite intercalations. In the western part of this unit large tonalite intrusions occur (Disgrazia massif, etc.).

2. *Insubrian fault zone of A. Spitz* (1919) *or Tonal line of Salomon-Calvi* (1890).—The fault zone runs from Giubiasco (south of Bellinzona, southeastern Switzerland) in an east-west direction north of the Val Tellina (northern Italy) and south of the Val Camonica. Farther east near Dinaro the fault is displaced toward the north by a cross-fault (the "Judicarian line"). The Insubrian fault zone continues farther eastward north of the granite massif of Brixen as the so-called "Puster line," which extends farther east into the "Drauzug" at least as far as the "Karawanken Mountains."

From Giubiasco the Insubrian fault continues westward into the "Cento Valli" and the "Zone du Canavèse," thence turning toward the southwest and following the east side of the "Sesia Lanzo zone" (root zone of the Pennine nappes). West of Lake Como (northern Italy) the fault zone is more commonly known as the "Jorio line of R. Staub"; east of Tirano it is known as the "Tonal line" of Salomon-Calvi.

The Insubrian zone is characterized by much mylonitization, which is greatest on the north side. Between individual mylonitic zones may be seen wedges, composed of Triassic, Permian, and Upper Carboniferous rocks, which originally covered the crystalline rocks farther south. Pre-Permian granite intrusions (the "Gneiss chiari") along the Insubrian fault zone indicate that this was a line of weakness even in Paleozoic time.

3. *Orobic metamorphic zone.*—In the east (probably Paleozoic) phyllites dominate, with few marble intercalations; in the west garnet-staurolite gneisses and garnet-mica schists occur, with few marble but many amphibolite intercalations. These amphibolite intercalations increase westward and become abundant in the "Ivrea zone."

4. *Orobic fault zone of C. Porro.*—In the central part of the Lombardy Alps, the Orobic fault zone runs from Bellano (at Lake Como), south of the Corno Stella Mountains, northeast of Mount Venerocolo into the Oglio Valley near Lava. This northeast part is often called the "Gallinera line" of R. Staub. The fault zone breaks through the Adamello group (tonalite massif) and continues probably south of the Dolomites as the "Val Sugana line." West of Lake Como the fault runs from Acquaseria, via Sasso Grande, Manno, and Cremenaga (in the Tresa Valley) to Bedero Val Travaglia (near Lake Maggiore), crossing the lake to Meina. The Orobic fault zone also contains pre-Permian granite intrusions (the "Gneiss chiari") and, in addition, young intrusions (near Baveno, Adamello group, etc.) which have accompanied the Tertiary deformation.

5. *Orobic and Lugano Alps.*—In the central parts the Orobic Alps are mainly composed of strongly imbricated Permian and Triassic sediments; to the east and west the younger Mesozoic sediments dominate. The Permian is mainly a volcanic effusive series. The Triassic is developed as thick limestone units with

marly intercalations in the Werfenian, Carnic, and Rhaetic. The Liassic is composed of black flaggy limestones, with red marbles in the upper part; the Dogger is composed of yellow and white limestones with radiolarite intercalations; the Malm consists of reddish (also greenish) limestones with red and greenish chert intercalations; the Lower Cretaceous is developed as a white limestone section, which changes into a flysch series in the Upper Cretaceous. In other words, there is a great similarity in the stratigraphic development of the western part of the central Toros geanticline and in the Orobic Alps (see Table II, Seydişehir and Seyhan Toros). The only fundamental difference is the lack of large-scale basic intrusions in the Orobic Alps at the end of the Jurassic and during the early Senonian. In this respect there is a greater resemblance to the eastern part of the southern Toros geanticline.

Also the Dalmatian coastal area and the western Peloponnesus were apparently developed in the Orobian facies without serpentine intrusions; eastward in the Vardar zone there were large serpentine intrusions.

Western Yugoslavia and western Greece are therefore probably the continuation both of the southern Toros geanticline and of the Orobic Alps. A fault zone similar to the "Orobic fault zone" occurs in eastern Turkey between the Siirt-Beytuşşebap zone (southern Toros geanticline) and the Bitlis-Hakkari Toros (central Toros geanticline). In addition, the northeast-southwest–directed blocks in the coastal plain southeast of Adana, near the Gulf of Iskenderun, indicate regional faulting between the central and the southern Toros geanticlines. In Greece and Yugoslavia the contact between the Vardar zone in western Greece seems to be an abnormal fault contact with large overthrusts similar to the Orobic faults.

If we consider this "Orobic fault zone" to be a regional one, our previous assumption about a continuation of the central Toros geanticline and Anatolides into the Vardar zone and western Rhodope massif seems to be correct. Both zones probably continue into the "Orobic metamphoric zone" (third tectonic unit) of the Lombardic Alps, which, however, is much thinner than its continuation in the Balkans. Also in the western part of the "Orobic metamorphic zone" (the so-called "Ivrea zone") many large amphibolitic intrusions penetrate the Paleozoic schists, comparable with the serpentine intrusions of the central Toros geanticline.

The Tonal metamorphic zone, separated from the "Orobic metamorphic zone" by the Insubrian fault zone, can be compared with the eastern Rhodope massif of Bulgaria. According to this interpretation, Salomon-Calvi's assumption seems to be correct. The Insubrian fault zone might continue, indeed, from the Karawanken in Austria toward the Morava-Struma Valley in the Balkans. The thinning of the different zones north and south of this fault zone toward eastern Turkey and the northwestern Balkans is in agreement with the phenomena to be expected in a regional fold curving around an area of alternating plastic and brittle layers (so-called "exfoliating leaf-shaped folding of Seidl," explained in the writer's work on the mechanism of the geological undulation phenomena, etc. [Leyden: Sÿthoff Pub. Co., 1937], p. 25).

In the Sesia-Lanzo zone (northwestern Italy) and in the areas north of the Tonal metamorphic zone are located the roots of the upper Pennine nappes and of the lowest eastern Alpine nappes. Between these regions are large Eocene tonalite

intrusions (e.g., The Bergell-Disgrazia massif). In the writer's publication[8] the retrofolding hypothesis of Staub has been shown to be incorrect. The upper eastern Alpine nappes are without roots; they have only a *pays d'origine* near the huge tonalite intrusions. The rising basement blocks, which developed the Pennine nappes, derooted the eastern Alpine crystalline blocks and transported them northward. Large intrusions took place along the scar, which closed later because of the further narrowing of the geosyncline (for further details see pp. 175–77 of ftns. 7 and 8).

It is also northeast of the Rhodope crystalline zone in northeastern Bulgaria that large overthrusts were reported by E. Boncev.[9] They probably continue into the Rumanian Transylvanian Alps with their large overthrusts. If we continue the Transylvanian Alps into the Carpathian Mountains with its nappe structures and finally into the Swiss Alps, we must assume that the rigid zone between the Pontides and the Torides widens again in northern Yugoslavia and forms the Hungarian plain west and east of the nappe zone.

We assumed that the Karawanken fault zone continues into the Morava-Struma zone. This transition (if our assumption is correct) is probably not a simple, regular one. Instead, it is probably cut by large north-south cross-faults.

Our present analysis cannot be complete for lack of sufficient trustworthy geological data on the Balkans. But with the aid of the well-known areas in the southern Alps (systematically studies by Leyden University parties, under the leadership of Dr. B. G. Escher) and in western Turkey (studied by the M.T.A. Enstitüsü), we have been able to correlate the zones of these regions in accordance with the facts available. We realize, however, that this synthesis is still very hypothetical and therefore have not attached a geotectonic map to this article.

[8] *La Géologie du Valle del Bitto et la tectonique des Alpes lombardes*, pp. 255–58.

[9] "Aus der alpidischen Tektonik Bulgariens," *Zeitschr. f. bulg. geol. Gesellsch.*, Vol. XIII (1940).

OTHER REFERENCES USED IN PREPARING TABLES

BLUMENTHAL, M. "Zur Geologie der Landstrecken der Erdbeben von Ende 1942 in Nord-Anatolian und dortselbst ausgeführte makroseismische Beobachtungen (Osmancik-Erbaa)," *Maden Tetkik ve Arama Enstitüsü Bull. No.* 8 (1943), pp. 46–58.

BÖCK, H. DE.; LEES, G. M.; and RICHARDSON, F. D. S. "Contributions to the Stratigraphy and Tectonics of the Iranian Ranges," in J. W. GREGORY, *The Structure of Asia* (1929), chap. iii.

LEES, G. M. "The Geology of the Oil Field Belt of Iran and Iraq," in *The Science of Petroleum* (1938).

LEUCHS, K. "Das jüngste Grossbeben in Anatolien," *Geol. Rundschau*, XXXI, Heft 1/2 (1940).

NICOLESCU, J. V. *Gisements pétrolifères de la Perse* (1928).

———. *Gisements pétrolifères de l'Iraq.* (1929).

NOWACK, E. "Eine Reise im westpontischen Gebiet Anatoliens," *Zeitschr. f. Erdkunde*, No. 1/2, (1928), p. 14.

PAMIR, HAMID NAFIZ, and KETIN, IHSAN. "Das anatolische Erdbeben Ende 1939," *Geol. Rundschau*, Vol. XXXII, Heft 3 (1942).

PAREJAS, ED.; AKYOL, IBR. H.; and ALTINLI, E. "Le Tremblement de terre d'Erzincan du decembre 1939 (secteur occidental)," *Univ. d'Istanbul*, nouv. ser. No. 10 (1942).

SCHMIDT, C. "Die Erdölfelder des nördlichen Iraq," *Oel u. Kohle* (1941), pp. 287–97.

SEIDLITZ, W. VON. *Diskordanz und Orogenese der Gebirge am Mittelmeer* (1931).

TROMP, S. W. "Preliminary Compilation of the Stratigraphy, Structural Features and Oil Possibilities of South Eastern Turkey and a Comparison with Neighbouring Areas," *Maden Tetkik ve Arama Enstitüsü Publications*, Ser. A, No. 4 (1941).

WILSER, J. L. "Die geotektonische Stellung des Kaukasus und dessen Beziehungen zu Europa," *Zeitschr. d. Deutsch. geol. Gesellsch.*, Vol. LXXX (1928), pp. 153–94.

REVIEWS

Geomorphology: An Introduction to the Study of Landforms. By C. A. COTTON. 4th ed. New York: John Wiley & Sons, Inc., 1947; printed by Whitcombe & Tombs, Ltd., New Zealand. Pp. xii+505; figs. 473. $6.00.

The new fourth edition of this well-known text appears for the first time in an American edition. Revisions from the third edition, which appeared in 1942, are minor: About twenty new and improved photographs have been substituted for older illustrations; slight changes have been made in the text; and the reading references and Index have been brought up to date and enlarged. It remains one of the most lucid discussions of geomorphology available for an introductory course.

LELAND HORBERG

Geology and Ground-Water Resources of the Island of Hawaii. By H. T. STEARNS and G. A. MACDONALD. (Territory of Hawaii, Division of Hydrography, Bull. 9.) Prepared in cooperation with U.S. Geological Survey. Honolulu, 1946. Pp. xiii+363; pls. 54; figs. 60

Bulletin 7 of this series, *Geology and Ground-Water Resources of the Island of Maui, Hawaii*, was reviewed in the *Journal*, Volume LIII (1945), page 144. Bulletin 8, *Geology of the Hawaiian Islands*, by H. T. Stearns, appeared early in 1946. This is a shorter synopsis of the geology of the whole group of Hawaiian Islands and may be recommended for its broader scope. It is effectively and beautifully illustrated, some of the plates being in color, while the numerous geologic maps are introduced as text figures where they are most serviceable.

Hawaii, largest of the Hawaiian Islands, has been built up by lavas poured from five volcanoes, each with independent rift zones and individual geologic history. Consequently, the first half of Bulletin 9 is devoted to the geomorphology, geologic features, and history of these volcanoes—Mauna Loa, Kilauea, Hualalai, Mauna Kea, and Kohala—intensive studies of which have already contributed greatly to the science of volçanology. The concise but comprehensive summary treatment of each of these brings together in readily available form much valuable information. In fact, this is the only recent publication which presents a compilation of all that is known of the geology of the island of Hawaii. Incidentally, the authors bring out the fact that volcanism in Hawaii "is waning in common with volcanism elsewhere on earth."

An excellent chapter on the "Petrography of Hawaii," by Macdonald, and one hundred and fifty pages on the ground-water resources complete the volume.

R. T. C.

The Coastline of England and Wales. By J. A. STEERS. Cambridge: University Press, 1946. (Macmillan Co. agents for United States and Canada.) Pp. xvii+644; figs. 114; pls. 115+2 pls. in natural color. $9.50.

Although the material for this study was prepared for the British Ministry of Town and Country Planning, the book is strictly physiographical and in no sense a treatise on land use. The approach is primarily descriptive, i.e., physiographic rather than geomorphic.

An introductory section is followed by a chapter on the structure and physiography of England and Wales, which includes a comprehensive appendix on stratigraphical geology. This is followed by a general summary of shoreline processes. Beach drifting by wave action is considered much more important than currents in transporting materials. The next eight chapters form the main part of the book and contain detailed descriptions of the entire coastline. In the final three chapters the problems of Pleistocene and Recent vertical movements, coastal dunes, and salt marshes are discussed. Geologists will find the opening and concluding chapters particulary useful. The descriptive chapters will be of interest largely to travelers and those concerned with special areas.

LELAND HORBERG

Geological Investigation of the Alluvial Valley of the Lower Mississippi River. By HAROLD N. FISK. Conducted for the Mississippi River Commission, Vicksburg, Miss., December 1, 1944; War Department, Corps of Engineers,

U.S. Army. 4to; pp. 78; atlas, 33 pls., 11 tables, 80 figs.

This superb work of which, it is understood, only one hundred copies were printed is monumental in its importance in the field of geology. Many of the plates are colored maps in great detail, a square yard or more in area, and the data recorded on them not alone are from surface observations but include those from many thousands of deep-well borings. The study represents the labors of a large staff, both engineers and geologists, carried out mainly during four recent years. The practical aim has been the greater security of the inhabitants of the floodplain-delta region; and, as a result of new revetments on levees, some four million additional farmers have settled on the fertile plains.

The alluvial valley of the Mississippi, that below Cape Girardeau, Missouri, is a "valley within-valley," alluviated during the Pleistocene. During the earliest of the Pleistocene glaciations sea-level was several hundred feet lower than now, and the river channels had become deeply incised within the Mississippi embayment of the Coastal Plain, which extended as far north as Cape Girardeau. The resulting topography, now buried under the alluvium, is therefore rugged, and the bottoms of the trenches are in many places farther below the Tertiary plain than the exposed valley walls rise above it.

The valley outline is that of an elongated cornucopia, narrower from the Gulf to Natchez in Mississippi but widening to an open end at the north, with an almost straight northwest marginal contact with the Ouachita and Ozark highlands in Arkansas and Missouri.

The northern part of the valley has an average width of 70 miles and an elevation at the northern end of 350 feet and of 200 feet at the southern. All major tributaries except the Ohio enter from the west. The embayment is directly over an axis of downwarping throughout the northern part. This can be traced as a sinuous line southward as far as New Orleans, where it intersects the axis of an east-west trending downwarp—the Gulf Coast geosyncline.

A very remarkable structural fracture pattern is clearly revealed by the orientation of streams, both tributary and distributary. To quote Fisk:

> Those of the western tributaries, such as the White, Arkansas, and Red rivers, trend northwest-southeast; those of the eastern tributaries, such as Homochitto, Big Black and Yaluhusha rivers, trend northeast-southwest. These directions parallel the trends of the major fault zones of the region and show that the location of the tributary streams has been controlled by the regional structures.

The number of the faults of this rectangular region pattern is legion, and they are proved individually by the offsets revealed by many thousands of closely spaced deep-well borings which intersect the contact with the indurated rocks at the bottom of the embayment. There is probably no area anywhere in the world where deep drillings have been so closely spaced. Movements on these faults have occurred concurrently with the crustal subsidence under the weight of the accumulating delta sediments. That such movements are still continuing seems to be shown by the fault which appeared at the surface at Vacherio, Louisiana, in April, 1943, as well as by the fault escarpments which still remain from the great earthquake of New Madrid in 1811–12. A direct correlation is drawn also between the warping of the fracture system and the changes in trend of the successive deltaic increments.

The later history of the valley, that of alluviation since the entrenchment of the floor, is comprised in two major stages, the earlier recorded in the subsurface alluvium. The history of the later of these is marked by an alternation of rising and stationary sea-level with a lowering one. This history is recorded in a nest of four trenches, each bordered by a pair of terraces. These are found both in the Mississippi Valley and in those of its principal tributaries.

While the glacier of the first stage (the Nebraskan) was over a considerable part of North America, the sea-level was lowered and the Mississippi cut down its channel. During the deglaciation which followed, sea-level rose and alluviation produced the highest pair of terraces, the Williana terrace. The three succeeding glaciations (the Kansan, Illinoian, and Wisconsin) each brought about a lowering of sea-level, followed by a rise and heavy alluviation during deglaciation. These three lower terraces Fisk has designated the Bentley, Montgomery, and Prairie terraces, each with gravels at the base and grading upward through sands into clays at the surface.

Throughout this history the land to the northward had been upwarped. The maximum altitude of the Williana terrace is 350 feet, that of the Bentley 200 feet, of the Montgomery 100 feet, and of the Prairie 40 feet above the present floodplain of the river. All four terrace pairs slope gulfward; the uppermost, the Williana,

with the steepest gradient, the lowest, the Prairie, with the flattest. This is the convincing proof of their succession in age from top to bottom. This reviewer has had the prized opportunity of visiting the terrace series under the guidance of the author of the monograph.

WILLIAM HERBERT HOBBS

The Voyage of Captain Bellingshausen in the Antarctic Seas 1819–1821. Edited by FRANK DEBENHAM. Translated from the Russian. Hakluyt Society, 2d ser., Vol. XCI, pp. xxx +213. London: printed in Great Britain by W. Lewis; Cambridge: University Press, 1945. $15.

The appearance of this translation a full century and a quarter after the completion of the voyage is an event of importance in the history of polar exploration. The Russian original was not published until a decade after the return of the expedition. No copy of the original report had been discovered in this country and only two in Great Britain. A copy of the atlas is, however, in the Library of Congress. Two partial translations had appeared in Germany.

Bellingshausen's expedition was one of the greatest, as well as one of the earliest, to penetrate into Antarctic seas, and his discovery of Antarctic land in latitude 69° S. (Peter I Island) was antedated by but one Antarctic landfall, that by the American captain, Nathaniel B. Palmer, only thirty-three days earlier. The discovery of Palmer Land, now the Palmer Peninsula of the Antarctic Continent, was made on November 18, 1820, while Bellingshausen sighted Peter I Island on January 9, 1821. On February 6 Palmer's little sloop "Hero" had an accidental joining-up off Palmer Land with Bellingshausen's "Vostok" and "Mirnyi." The two captains had a meeting on the "Vostok," where they conversed through an interpreter. We now have the accounts of this conversation by both parties to it.[1] They are in perfect accord, though that of the Russian captain occupies less than a page of his narrative, while Palmer's story is much more complete. Palmer states that Bellingshausen appeared to be astounded when he displayed his chart and his log, and the Russian exclaimed: " 'What do I see and what do I hear from a boy in his teens—that he is commander of a tiny boat of the size of a launch of my frigate . . . . and sought the point I, in command of one of the best appointed fleets at the disposal of my august master, have for three long, weary, anxious years searched day and night for.' With his hand on my head he added, 'What shall I say to my master? What will he think of me? But be that as it may, my grief is your joy; wear your laurels with my sincere prayers for your welfare. I name the land you have discovered in honor of yourself, noble boy, Palmer's Land.' "

This part of the conversation is omitted in Bellingshausen's account, and Debenham, the editor of the translation, has devoted four of the twenty pages of his introduction to an acrimonious argument in an attempt to discredit Palmer as the discoverer of the Sixth Continent.

Priority in discovery is, of course, not to be settled by this report. Bellingshausen with little doubt regretted his impetuous speech, as he reflected that the right to name new lands belongs to the discoverer, and he knew he must win the approval of his august master.

That Palmer's Land was actually discovered on November 18, 1820, is proved by Palmer's log, now in the Library of Congress; also by the appearance of "Palmer's Land" on an American map of September 28, 1821 (see *Science*, Vol. 000 [June 23, 1939], pp. 000–00), and on official British Admiralty maps of November 1, 1822, and November 4, 1824. It was later that the Admiralty set up the claim that the same land had been discovered by Edward Bransfield, R.N., and named Trinity Land almost a year earlier than Palmer's discovery.

We learn from the translation that Bellingshausen's two sloops of war were well found and outfitted but that the captain was disappointed in failing to secure scientific personnel, especially naturalists. We have, however, the assurance of a distinguished ornithologist that Bellingshausen's own observations within that field were excellent and often brilliant.

An ardent admirer of Captain James Cook, Bellingshausen endeavored to make his own cruise supplementary. Where Cook had been forced by the pack ice to lay his course to the north, Bellingshausen made special efforts to maintain a more southerly cruise, in which he was generally successful. His meteorological observations were very valuable, and his determinations of position, checked by several observers, command the fullest confidence. The translation appears to have been well done, and the narrative is easy to follow.

WILLIAM HERBERT HOBBS

[1] For Palmer's account see "The Discovery of Antarctica within the American Sector as Revealed by Maps and Documents," *Trans. Amer. Phil. Soc.*, N.S., Vol. XXXI (January, 1939), pp. 18–23.